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San Francisco Bay Long-Term Management Strategy (LTMS) for Dredging and Disposal

Report 2
Baywide Suspended Sediment Transport Modeling

by Allen M. Teeter, Joseph V. Letter, Jr., Thad C. Pratt, Christopher J. Callegan, William L. Boyt

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Report 2 of a series

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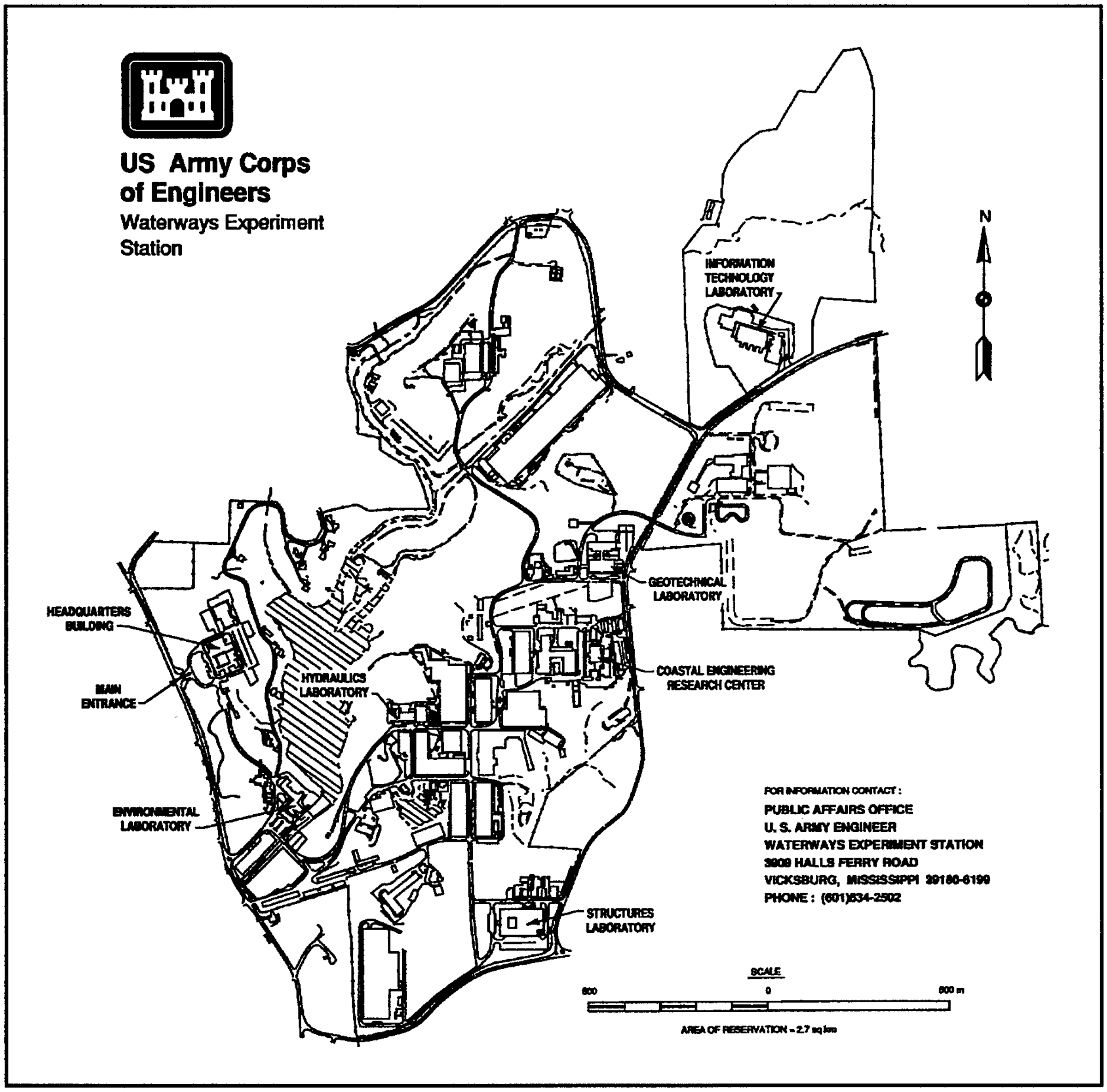

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Preface

The work described in this report was performed by the Hydraulics Laboratory (HL) of the U.S. Army Engineer Waterways Experiment Station (WES) during the period of March 1992 through November 1993 as a part of the San Francisco Bay Long-Term Management Study (LTMS). The work was conducted for the U.S. Army Engineer District, San Francisco (CESPN). This is the second of a series of four reports. Report 1 covers hydrodynamics; this report, Report 2, covers baywide suspended sediment transport; Report 3 describes disposal modeling; and Report 4 describes field data collection procedures.

The study was conducted under the direction of Messrs. Frank A. Herrmann, Jr., Director, HL; Richard A. Sager, Assistant Director, HL; William H. McAnally, Jr., Chief, Estuaries Division (ED), HL; and George M. Fisackerly, Chief, Estuarine Processes Branch (EPB), ED. Mr. Thad C. Pratt was Project Manager, with technical team leadership provided by Messrs. Joseph V. Letter, Jr., and Allen M. Teeter, all of EPB.

The two-dimensional modeling was performed by Messrs. Letter, Pratt, Christopher J. Callegan, EPB, and William L. Boyt, EPB. The three-dimensional modeling was performed by Mr. Letter. The analysis of the model results was performed by Messrs. Teeter, Letter, and Pratt. This report was prepared by Messrs. Teeter, Letter, Pratt, Callegan, and Boyt.

Dr. Robert W. Whalin was Director of WES at the time of publication of this report. COL Bruce K. Howard, EN, was Commander.

1 Introduction

Background

The San Francisco Bay region navigation channels require annual dredging of approximately 6.2 million cubic meters (8 million cubic yards) of sediment. Economical and environmentally sound disposal of those sediments plus new-work dredged material are goals of the Long-Term Management Strategy (LTMS). The LTMS plan (Ogden Beeman and Associates, Inc., 1991) was developed by a group of agencies led by the U.S. Army Corps of Engineers, U.S. Environmental Protection Agency Region IX, San Francisco Bay Regional Water Quality Board, and San Francisco Bay Conservation and Development Commission.

Task 3 of the LTMS plan is to identify and collect additional data with respect to environmental, engineering, and economic factors to enable initial screening of the list of possible disposal alternatives and elimination of infeasible alternatives. Under Task 3, Work Elements F, Behavior and Fate of In-Bay Disposed Material, and H, Evaluate Alternative In-Bay Disposal Sites, call for a modeling needs assessment and subsequent development of a three-dimensional (3-D) numerical model for sediment transport in the bay, including necessary field data collection to verify the model.

The modeling needs assessment was performed by the In-Bay Work Studies Group, one of several interagency work groups established under the LTMS. The following recommendations (U.S. Army Engineer District (USAED), San Francisco, 1992) were made by the work group:

"1. The LTMS Study Plans's goal to satisfy decision-maker's information needs regarding dredged sediment fate and transport from the existing, and any potential new, in-bay disposal sites with a fully verified sediment transport model during the 1993 period is not possible. This goal must be revised to reflect what can be accomplished by breaking it into interim degrees of completion as physical system understanding and numerical model verification process. Providing some useful information by the beginning of 1993 appears achievable if strategies for meeting LTMS needs utilize available numerical tools.

"2. To make decisions in 1993 (i.e., during the short-term) will require that decision-makers accept greater uncertainty from model predictions that will be necessary over the long-term. Utilizing the existing DIFID and TABS-MD models, augmented with limited field work, decision-makers will be provided with simulations that are between 50 to 80 percent reliable in order to proceed with their decisions regarding future in-Bay disposal under the LTMS.

"3. Long-term (i.e., several years) field data collection and analysis of physical processes controlling sediment transport will be necessary to improve model calibration and verification and will lead to increased reliability of model simulations provided to decision-makers regarding sediment fate and transport in the future.

"4. Activities should be initiated immediately in support of developing and producing model predictions during the near term (1993) with WES as well as simultaneously begin long-term, field data collection with USGS. The field data collection should continue over the coming years beyond the LTMS and be augmented with analyses deemed appropriate for developing a sound understanding of sediment transport processes. All activities should be coordinated and strive to meet the long-term requirements for providing a fully verified numerical sediment transport model for the San Francisco Bay and Delta system."

A scope of work for modeling sediment transport in the bay was developed from the modeling needs assessment recommendations and in consultation with the In-Bay Studies Work Group. Likewise, a scope of work for field data collection was developed in close consultation with the In-Bay Studies Work Group. The overall scope attempted to balance the needs for field data with which to verify models against model development and to fit both field and modeling work to the objectives listed previously and within the time and funds available to accomplish the work.

Scope

This report series presents the pertinent features of San Francisco Bay, the technical approaches employed to conduct the field data collection and sediment modeling, the sediment model used, the results of model verification, and an analysis and interpretation of field and model results. Near-field modeling of dredged material disposal was performed by the San Francisco District and used in the far-field disposal modeling presented in Report 3. The reports of the series are as follows:

a. Report 1, "Hydrodynamic Modeling."

b. Report 2, "Baywide Suspended Sediment Transport Modeling."

c. Report 3, "Dredged Material Placement Alternatives."

d. Report 4, "Field Data Collection."

Report 1 presents the overall model development and the hydrodynamic verifications for both the two-dimensional (2-D) and 3-D model applications. In addition, this report provides a comparison of the 2-D and 3-D circulation patterns as an evaluation.

The present report, second in a series of four, presents the results of a field data analysis and numerical modeling investigation of suspended material movement as it relates to dredged material disposal in San Francisco Bay, California. It comprises portions of Work Elements 3F and 3H, the behavior and fate of disposed material and environmental effects, respectively, of the "Long-Term Management Strategy (LTMS) for Dredging and Disposal-San Francisco Bay Region-Study Plan" (Ogden Beeman and Associates, Inc., 1991).

Report 3 describes the disposal simulation design and test results for the placement of dredged material in the alternative disposal sites.

The field data collection effort performed to support the modeling work is described in Report 4. The data monitoring techniques are fully described along with cataloging and summarizing of the data obtained.

Objectives

The overall objectives of this work were to

a. Determine the dispersal and probable fate of dredged material from existing disposal sites.

b. Predict the dispersal and probable fate of dredged material from potential disposal sites.

c. Provide additional information on the sediment budget for the bay system, including net sediment fluxes and tidal exchange.

d. Provide guidance on use of model results to manage dredged material disposal sites.

e. Provide a framework and work toward a future verified 3-D numerical model of San Francisco Bay hydrodynamics and sediment transport.

The degree to which these objectives could be achieved was constrained by available field data, current modeling technology, and the time and funds available to accomplish the work.

Previous Work

The sediment modeling work presented here is the culmination of modeling experience gained by the U.S. Army Engineer Waterways Experiment Station (WES) in a number of previous studies. Previous work in San Francisco Bay has led to the current model study and had a direct influence on the technical approach.

A preliminary sediment transport model was developed and verified to the low-flow conditions of September 1988 (Hauck et al. 1990). An earlier study (Pankow 1988) developed a hybrid model consisting of numerical near-field disposal and far-field transport components. Disposed materials were tracked for 3 to 4 hr following discharge. Another study (Teeter 1987) performed laboratory erosion tests on deposited and remolded dredged sediment beds to determine erodibility. Results of this study were used with field velocity data to predict the capacity of the Alcatraz disposal site to disperse disposed materials. Trawle and Johnson (1986a, 1986b) dealt with the prediction of near-field behavior from the instant of disposal through a few hundred seconds until most of the material had descended to the bed. A numerical disposal model was used for this purpose.

Technical Approach

The LTMS plan called for a full 3-D sediment transport model to address the LTMS objectives of Work Elements 3F and 3H as described in the section, "Background"; however, the modeling needs assessment (USAED, San Francisco, 1992) recognized that the time and funds available did not permit development and verification of such a model. The modeling approach endorsed by the assessment was to use available 2-D and 3-D models in a combined approach to provide the best possible answers within the constraints.

The overall approach to meeting the objectives was to

a. Collect field data to demonstrate sediment fluxes in the areas adjacent to the existing disposal site.

b. Increase spatial resolution and 3-D coverage of an existing 2-D/3-D numerical hydrodynamic and salinity transport model, verify it to field observations, and use it to compute the path of a conservative (nondepositing) tracer from the disposal site(s).

c. Increase resolution of existing 2-D (depth-integrated) hydrodynamic and sediment transport models, verify them to field data, and use them to compute the path and deposition/erosion of sediment transported out of the disposal site(s).

d. Use the 2-D and 3-D model results in combination to illustrate the differences in the two approaches and provide a good estimate of the path and fate of sediments transported out of the disposal site(s).

Step *b* of this approach provided fully 3-D tracer results, which can capture vertical circulation patterns created by density differences between river water and seawater, but which cannot reproduce tidal pumping of sediments created by the deposition/resuspension cycles of sediment movement under asymmetrical flows. Step *c* provided 2-D sediment model results, which can capture the tidal pumping effects, but not the vertical circulation. Comparing the results from these steps gives a better approximation of sediment fate and an estimate of the degree of error/uncertainty in the results. Those results plus the results from step *d* are presented in Report 3 (Letter et al., in preparation).

Finally, the 2-D and 3-D models generated by this work are fully compatible with the goal of a future fully 3-D sediment transport model of the bay system. The model constructed here can be extended to incorporate 3-D sediment transport, deposition, and erosion, and all of the work described here will have been useful.

2 Description of San Francisco Bay

The purpose of this chapter is not to provide a comprehensive reference to fully document the physical processes within San Francisco Bay. However, a brief overview sufficient to identify the features of the system pertinent to dredged material placement is warranted. For a more complete description of the system, please see the Bibliography.

San Francisco Bay (Figure 1) comprises several embayments created from valleys formed by tectonic downwarping and faulting during the Pliocene epoch (USAED, San Francisco, 1979). The bay system has been filling with alluvial sediments over the past several centuries at accelerated rates. The bay system is fed by several major tributaries that drain the majority of central California, about 111,400 sq km (43,000 square miles). The two primary tributaries are the Sacramento and San Joaquin Rivers, which join within the very complex delta (Figure 2), which is a maze of tidal channels and sloughs that connect with the bay system through Suisun Bay and Carquinez Strait. Other minor tributaries supply only limited fresh water to the bay system but provide tidal connections to some significant wetland areas. The estuary is spectacular in natural beauty, and in ecological, cultural, and commercial importance.

Tidal Propagation

The tides in San Francisco Bay are mixed with a large diurnal inequality. Mean tide range at the Presidio at San Francisco is 1.77 m (5.8 ft) with average spring tides of approximately 2.44 m (8.0 ft). The tide range is amplified in South Bay (2.65-m (8.7-ft) mean spring tide) with the development of some standing wave characteristics (Figure 3). The tide range through the northern part of Central Bay and South Bay remains similar to the range at Presidio with the combined effects of frictional damping and geometrical influences on a progressive wave. As the tides propagate through Carquinez Strait and Suisun Bay and into the delta, the tidal amplitudes are reduced to a mean tide range of 1.34 m (4.4 ft) at Chipps Island at the upper

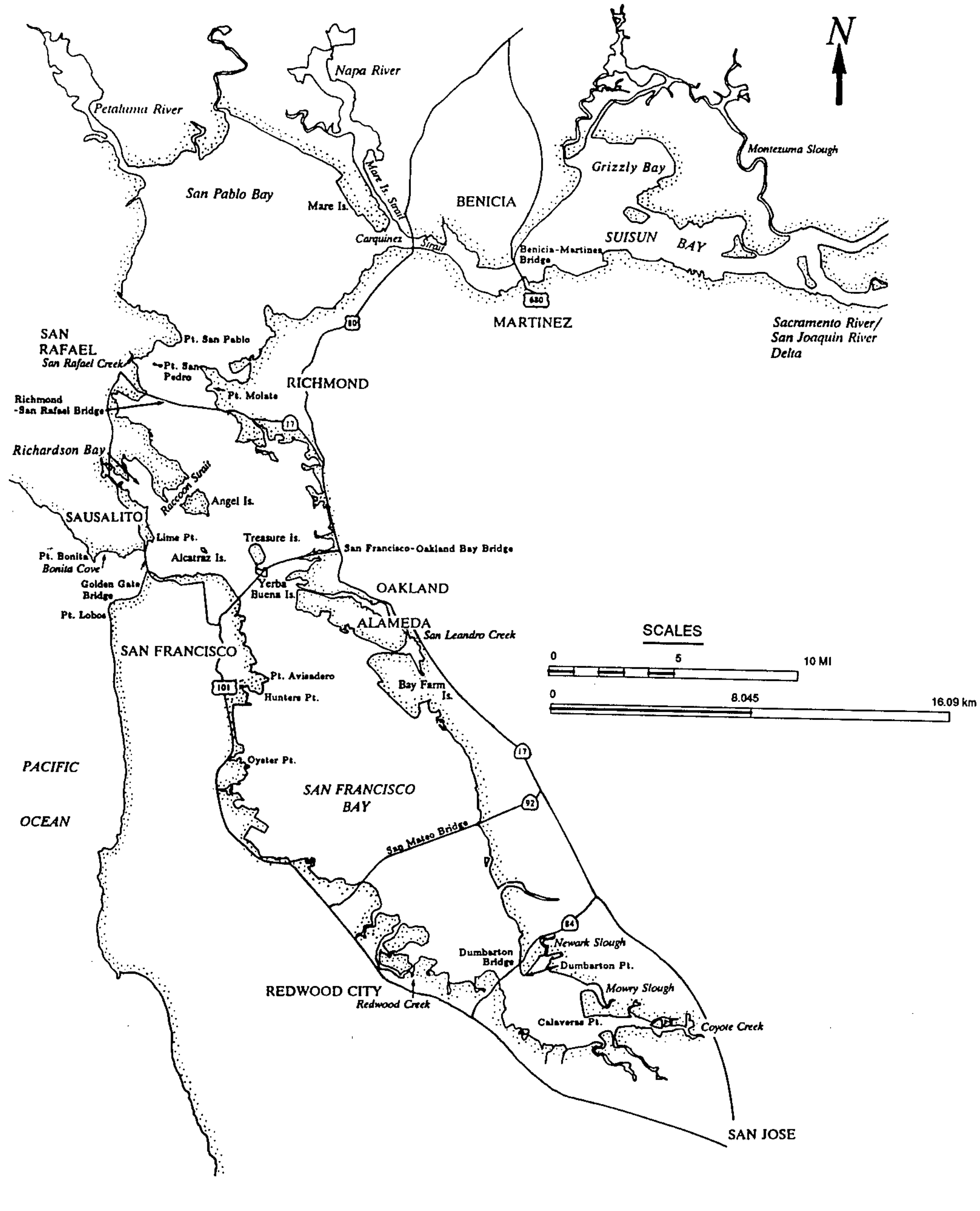


Figure 1. San Francisco Bay and vicinity

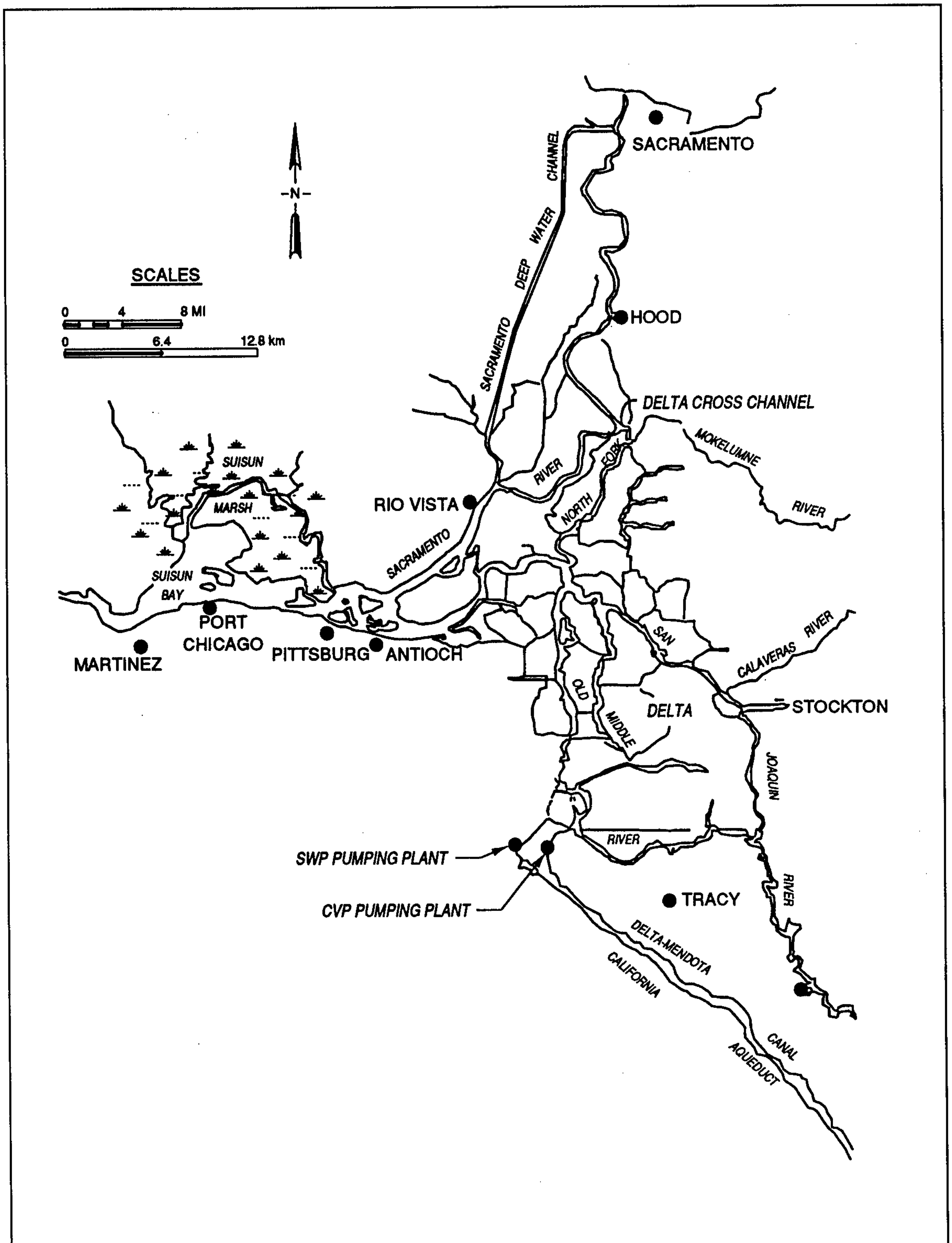


Figure 2. The San Francisco Bay-Delta region

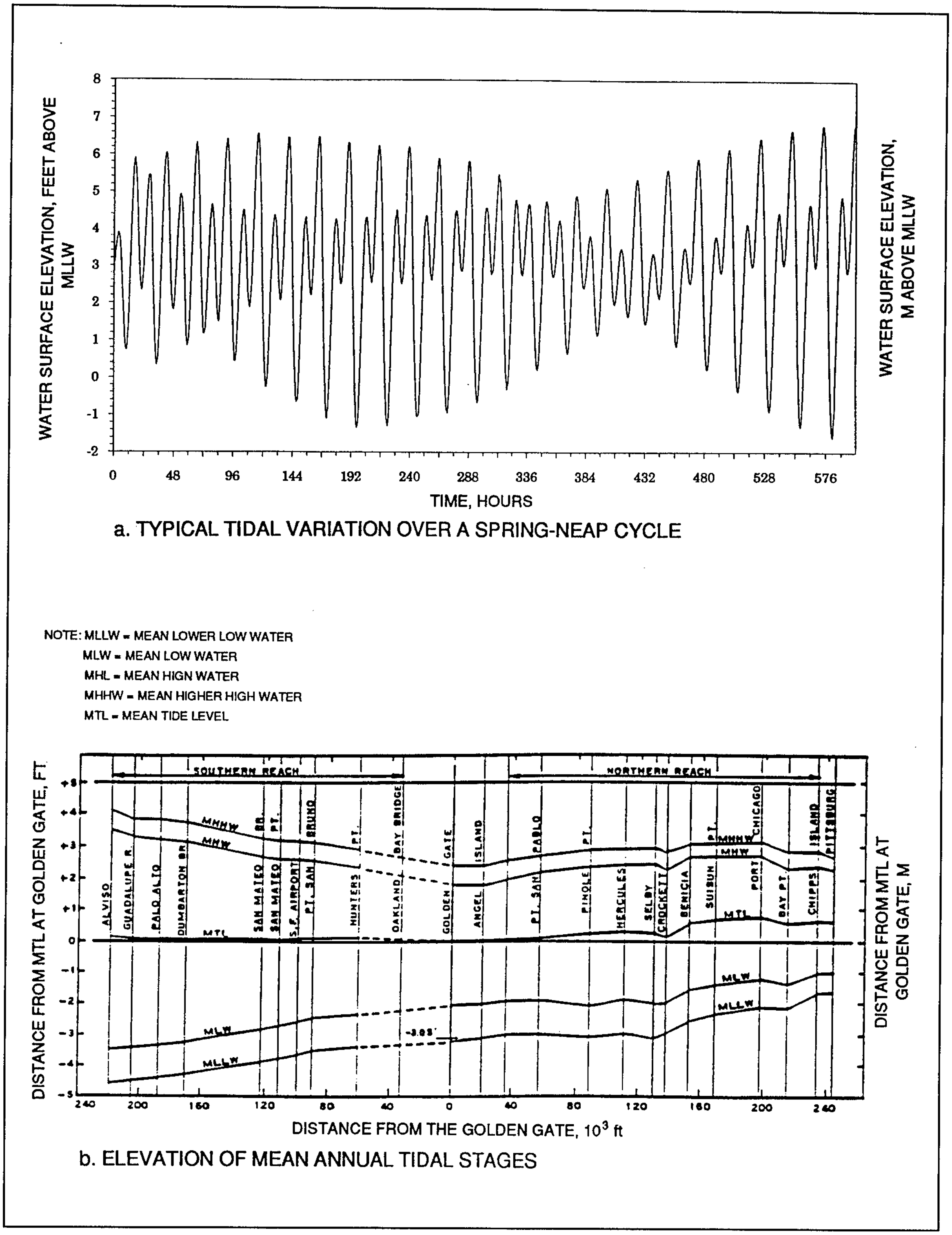


Figure 3. Tides, San Francisco Bay

end of Suisun Bay. For a comprehensive description of the tide in the bay, Welch, Gartner, and Gill (1985) document the tidal harmonics throughout the system.

Hydrology

The freshwater inflow to the study area is dominated by the flows that are delivered from the delta (Figure 2). The mean "net delta outflow" (NDO) is approximately 340 cu m/sec (12,000 cfs). However, during recent years, the area has experienced exceptionally low freshwater supplies.

The freshwater supply in the Sacramento-San Joaquin Delta is an extremely valuable and controversial resource. Extensive agricultural tracts have been developed by diking and irrigation. As a result, withdrawals for irrigation and municipal water supplies are the same order of magnitude as frequently occurring low river flows.

The overall sediment supply to the system is derived largely from the upper tributaries. However, the average annual sediment supply is small compared to the in situ active bed supply that is easily mobilized by high tide ranges or local wave energy.

Meteorology

Local rainfall is relatively low by U.S. standards and can be ignored as far as its contribution to the overall hydrology of the bay and tributaries. The winds over the bay are very complex and are greatly influenced by the surrounding mountains. Numerous meteorological gaging stations (Figure 4) within the bay community are coordinated by the Bay Area Air Quality Management District (BAAQMD). However, all of these monitoring stations are located on land, and many are located upslope at fairly high elevations. No comprehensive wind data are available over open water within the bay. This is typical of most estuaries, and adjustments to land wind measurements for boundary layer effects were made by this study to estimate winds over the bay. The predominant wind directions in the bay area are from the west to south with average wind speeds from 4 to 5 m/sec (8 to 10 knots).

Wave Climate

Wave conditions within the bay are controlled primarily by local winds. Swell from the Pacific Ocean may create severe conditions in the vicinity of the Golden Gate Bridge, but conditions are generally dominated by locally generated wind waves. The waves exhibit diurnal variation with the daily wind climate. When the wind direction aligns with the long axis of the bay

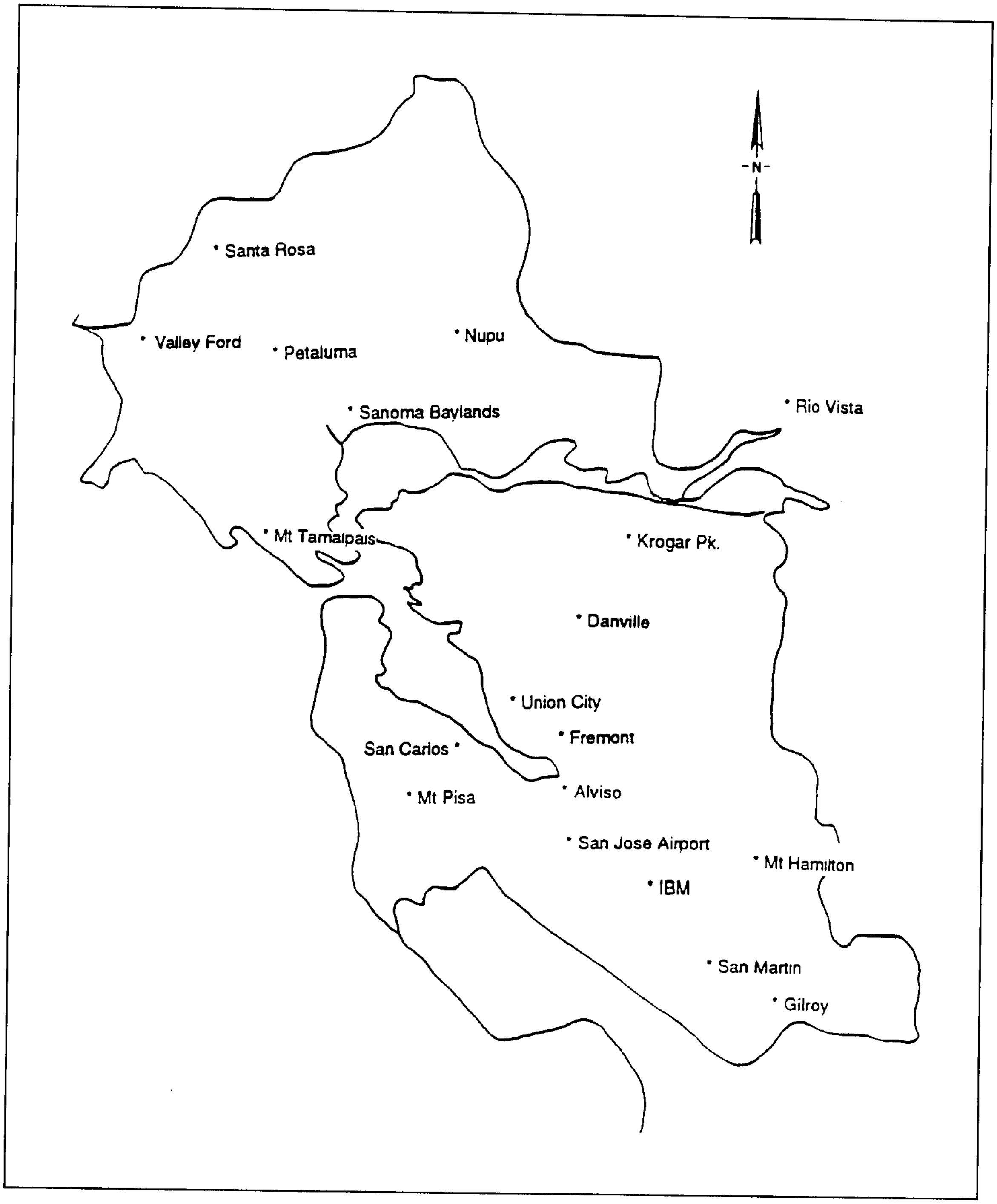


Figure 4. BAAQMD meteorological station locations

(north-northwest to south-southeast) the wave climate is most severe. Local chop is generated as winds are steered by the adjacent mountain ranges into local canyons. For example, westerly winds coming off the shore near Candlestick Park in South Bay create a local zone of severe waves that are not as severe further to the south where the wind fetch is comparable. Meter-high waves over fairly extensive portions of the bay are a common occurrence.

Federal Projects

The primary Federal projects in the study area that use dredged material disposal facilities are presented in Table 1 along with their maintenance dredging requirements (Ogden Beeman and Associates, Inc., 1992).

Sedimentation Environment

Sedimentation and suspended sediments in the San Francisco Bay have received only limited attention compared with other parameters and hydrographic variables such as water levels, currents, and salinity. Most field surveys have either not included sediment and suspended sediment measurements or have not emphasized such measurements. The complexity of suspended sediment movement in an estuarine environment makes quantitative study of sediment movement a difficult and costly undertaking. However, ample evidence does exist to provide qualitative understanding of sediment and suspended sediment behavior.

There is general agreement among most researchers regarding the qualitative behavior and characteristics of riverine sediment loading to the estuary including aggregation, deposition, suspension, erosion, and circulation of sediments in the San Francisco Bay system. To provide background to baywide suspended sediment behavior, a synopsis of some of the available literature on general baywide sediment is provided in Appendix A, which presents a short bibliography on baywide sedimentation.

In a study of sedimentation in Mare Island Strait, an artificially deepened portion of the lower Napa River at Carquinez Strait, a seasonal sedimentation pattern in the San Pablo Bay-Carquinez Strait study area was discovered. Despite higher suspended sediment concentrations in bay waters in the winter, much of the deposition in Mare Island Strait occurs during the summer. It was determined that deposition during the winter occurs in the shallow bays and mud flats. The almost daily summer patterns of high midmorning to late afternoon winds produce wave action that resuspends these winter-deposited sediments. Once the sediments are resuspended, ambient currents move them to relatively quiescent areas such as Mare Island Strait, resulting in deposition in these areas.

Table 1
Federal Dredging in San Francisco Bay, 1955-1990

Project	Total Dredging 1,000 cu yd	Number of Years Dredged	Average Annual Dredging, 1,000 cu yd	
			36-year Average	For Number of Years Dredged
Islais Creek	194	1	5	194
Mare Island Strait	58,485	35	1,625	1,671
Napa River	1,653	3	46	551
Oakland Inner/Outer	20,958	33	582	635
Petaluma River Channel	3,818	11	106	347
Pinole Shoal Channel	9,380	14	261	670
Redwood City Harbor	11,492	21	319	547
Richmond Inner/Outer	28,161	35	782	805
San Francisco Harbor	1,977	13	55	20
San Leandro Marina	717	3	20	239
San Rafael Creek	1,045	6	29	174
Suisun Bay Channel	5,454	28	152	195
Navy Projects				
Alameda NAS	21,898	25	608	876
Mare Island	9,321	18	259	518
NCS Oakland	2,362	6	66	394
NSY Hunters Point	838	6	23	140
NSY Mare Island	3,301	6	92	550
NAS Moffett Field	229	2	6	115
NWS Concord	613	13	17	47
Point Molate Depot	2,539	18	71	141
NS Treasure Island	729	2	20	365

Note: Data from Ogden Beeman and Associates, Inc., 1992.
To convert cubic yards to cubic meters, multiply by 0.77.

These early observations have been substantiated by subsequent research and field data evaluation, and a baywide sediment transport pattern similar to the Mare Island Strait results emerges from the literature.

Approximately 80 to 85 percent of the riverborne sediment to San Francisco Bay originates from the Sacramento-San Joaquin River basin and over 80 percent of this riverborne sediment is contributed during the

period of high freshwater inflow in winter and early spring. Ogden Beeman and Associates, Inc. (1992), describes these sources and their historical trends.

The measured suspended sediment concentrations indicate a strong pattern of maximum suspended sediment levels in San Pablo and Suisun Bay areas (the null zone is normally located in either of these bays), the lowest levels near the Golden Gate in Central Bay, and somewhat elevated levels in South San Francisco Bay (South Bay). The seasonal patterns reported by all researchers was riverborne sediment supply and deposition during the winter and sediment resuspension, transport, and redeposition during the summer.

3 Technical Approach

Modeling Strategy

The modeling strategy adopted for the LTMS study reported here was to expand the 2-D sediment transport modeling begun in 1988 by WES (Hauck et al. 1990) to include verification of the model to a higher NDO condition. This approach was built upon additional field data collection to obtain the necessary data for that high-flow verification. The sediment transport modeling was limited to 2-D, while a 3-D numerical hydrodynamic model was developed for the purpose of defining the applicability and limitation of the 2-D sediment transport model to the study area. The 3-D hydrodynamic model development is a step ultimately toward a future 3-D sediment transport model.

The sediment modeling was limited to suspended fine-grained materials, deemed to be of greatest concern with respect to turbidity and adsorbed trace contaminants. No attempt was made to quantify or predict the movements of sand and coarser material, which tend to move near the bed as bed load. Over time, coarse material transport can have an important effect on morphology, especially in Central Bay, which contains extensive coarse-material bottom areas. However, the majority of dredged material disposed in open waters is fine-grained; therefore, only fine-grained materials were modeled.

The earlier sediment modeling work illustrated the significance of the wave environment on the resuspension of deposited material from the shallow areas of the system. Therefore, the present study included the development of wind and wave models of the bay to be used to more accurately estimate wave energy throughout the system.

Field Data Collection

The original intent for the data collection program was to obtain data for higher net delta outflows. However, because of delays in study initiation, it was necessary to either delay the entire field data collection program until the following high-flow season or proceed with whatever flow could be obtained.

The overall study schedule precluded further delays. The WES field data collection program was conducted during the period of 6-28 June 1992. Report 4 of this report series describes field data collection. There were no high flows during the study execution. Further discussion of this limitation will be presented later.

The data collection included the data ranges shown in Figure 5. Each data range had a vessel equipped with an Acoustic Doppler Current Profiling (ADCP) meter. Over the survey period these vessels collected cross-sectional current velocity data, generally during daylight hours. In addition to the ADCP data, each range was sampled periodically for suspended sediment concentrations and salinity measurements.

Water-surface elevation recorders were located at several locations in the system (Figure 5) as well as 11 moored in situ recording current meters (Figure 6). Automatic programmable pump samplers were installed to provide some long-range integrated samples for laboratory analysis of salinity and suspended sediments.

Other data collected by WES in September 1988 (Hauck et al. 1990) were used in the present study. That data sampling focused on a detailed intensive survey conducted over a 25-hr period. Data collected were water-surface elevations, salinities, suspended sediment concentrations, and current velocity profiles. The salinities and sediment concentrations were determined by laboratory analysis of physical water samples obtained by pumping from sample depth using plastic tubing connected to a weighted cable attached to a gaged winch on the vessel. The current velocities and directions were obtained from impeller-type velocity meters and vaned magnetic directional indicators mounted at the bottom of the weighted cable. The 1988 data ranges and tide stations are presented in Figure 7.

Hydrodynamic Modeling

The hydrodynamic modeling needed to support the sediment transport study was performed using the RMA-2 finite element model, a component of the TABS-MD modeling system of the U.S. Army Corps of Engineers. The RMA-2 model is a depth-averaged homogeneous hydrodynamic model (Thomas and McAnally 1985). See Appendix A of Report 1 of this series for a full description. The hydrodynamic mesh is shown in Figure 8. The model mesh developed for the sediment transport support was also converted into a 3-D hydrodynamic model for the purpose of evaluating the 3-D effects on circulation. For the 3-D modeling simulations RMA10 was used, which is the 3-D version of the TABS-MD technology. See Report 1 of this report series for details on the hydrodynamic modeling.

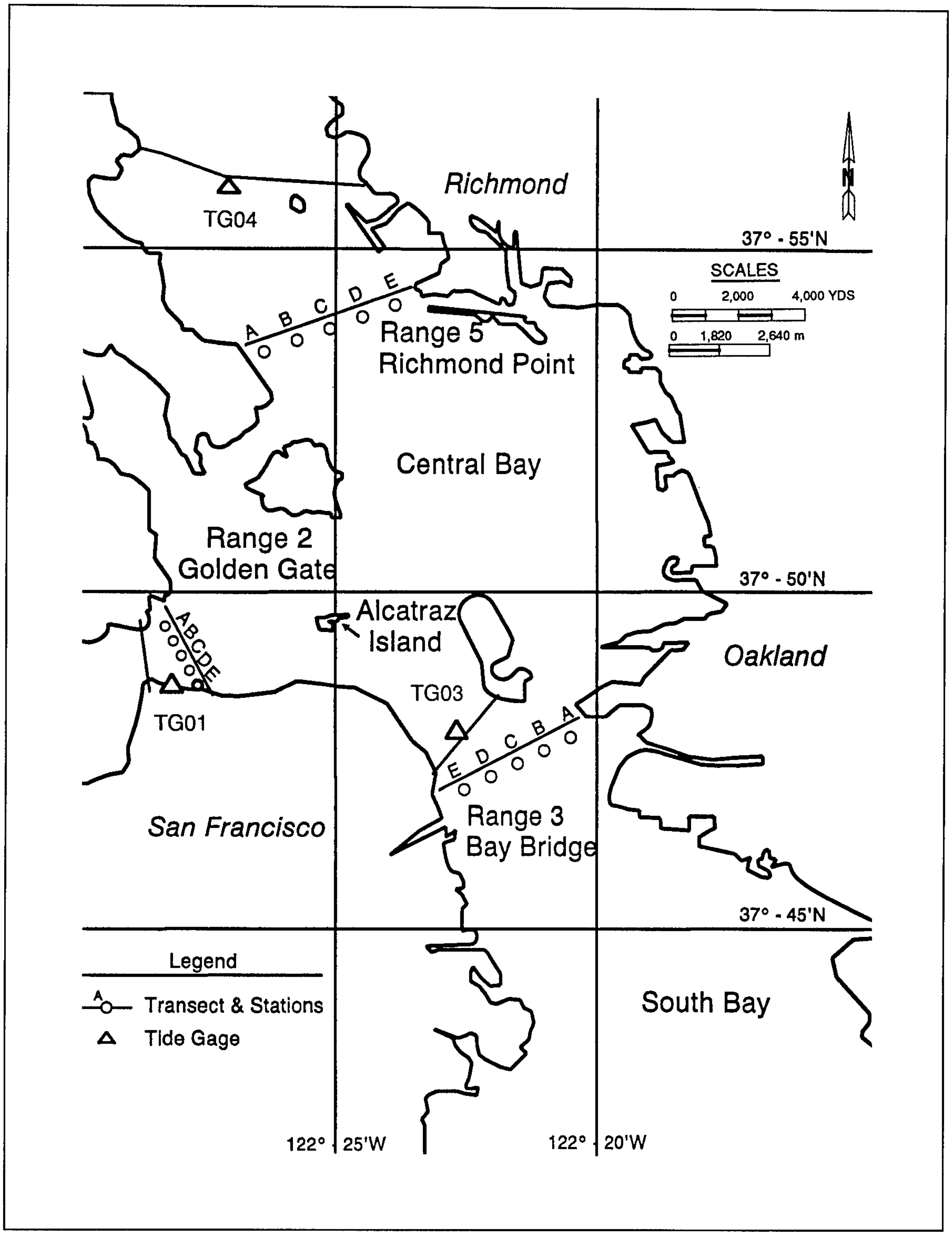
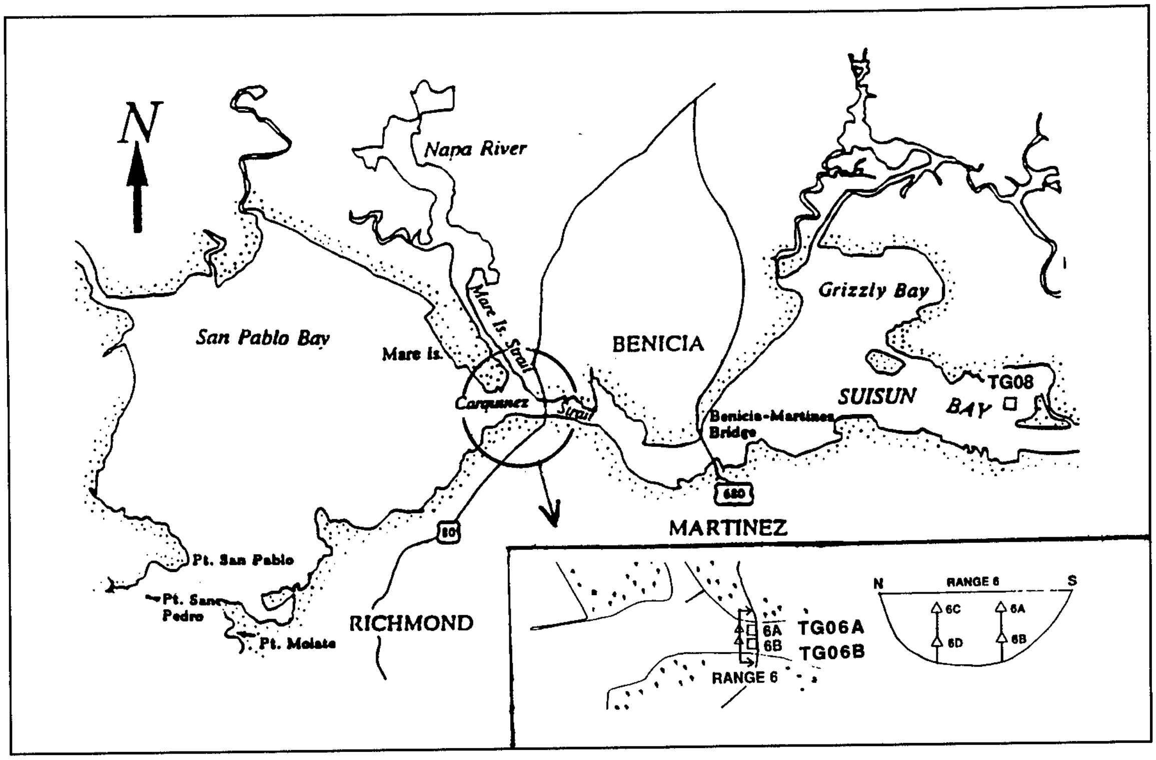
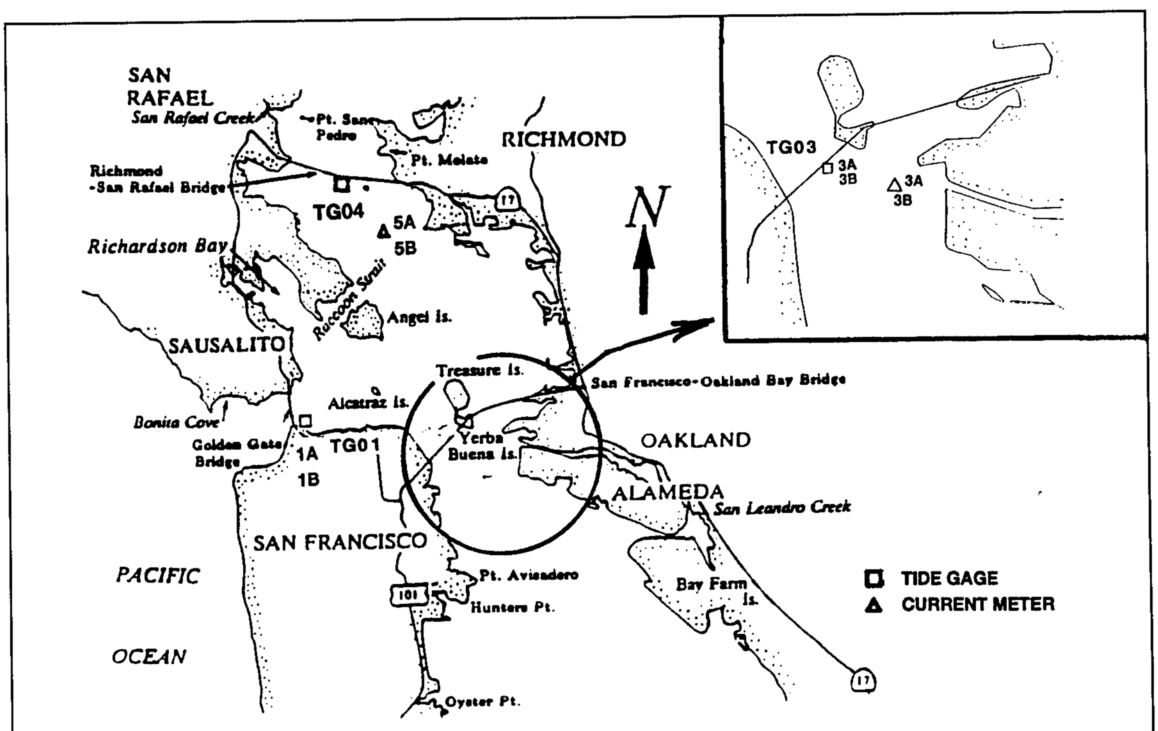


Figure 5. Sampling ranges for the 1992 survey

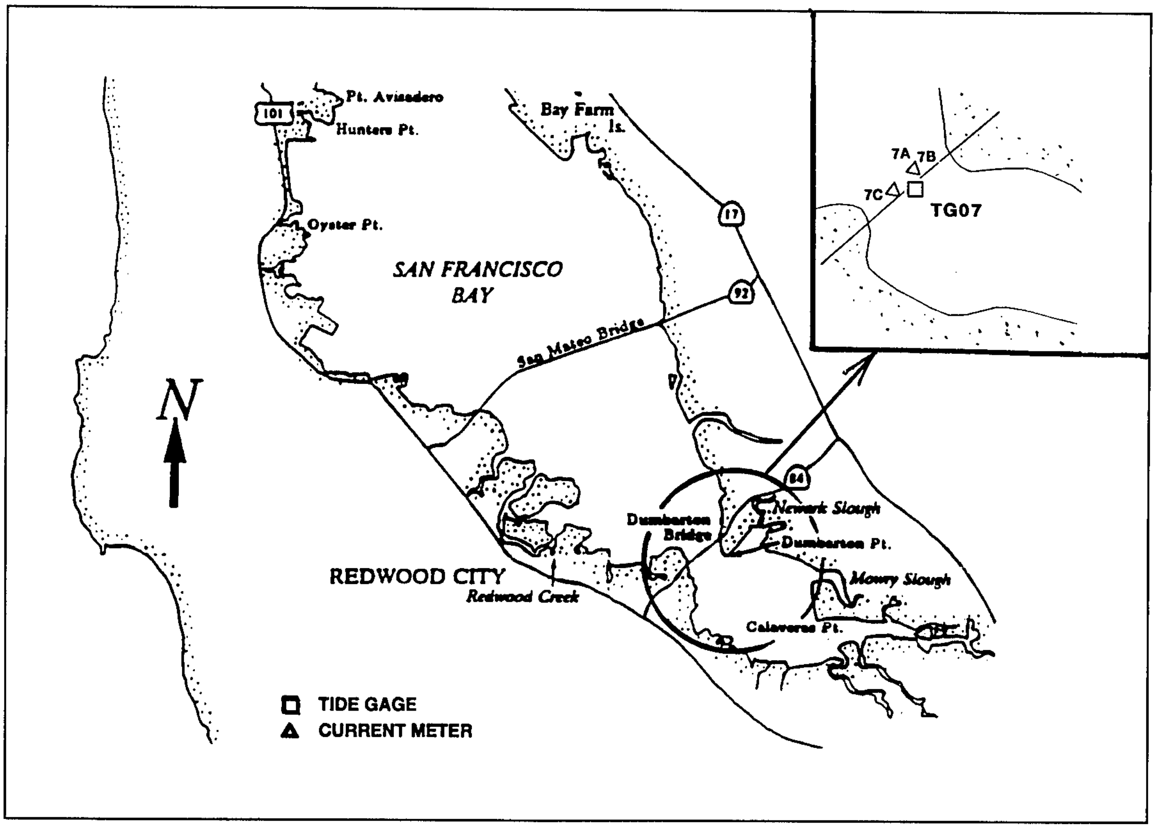


a. Upper Bay monitoring sites



b. Central Bay monitoring sites

Figure 6. Data monitoring sites for the 1992 survey (Continued)



c. South Bay monitoring sites

Figure 6. (Concluded)

Wind Modeling

The wind model was developed under contract with Dr. Donald Resio, then of the Florida Institute of Technology, Melborne, FL. The wind model performs a kinematic analysis of the winds, based on available meteorological stations around the bay. The model develops an interpolated surface wind field over a 100-m finite difference grid (Figure 9) incorporating the land-sea interactions. Details are provided later in this report.

Wave Modeling

Wave energy is estimated by the application of a parametric wave model to define the temporal and spatial variations in the wave energy environment within the study area. The wind forcing for the wave model was taken from the wind model described in the preceding paragraph. The wave energy and dominant wave period are then converted into a significant wave height over the model.

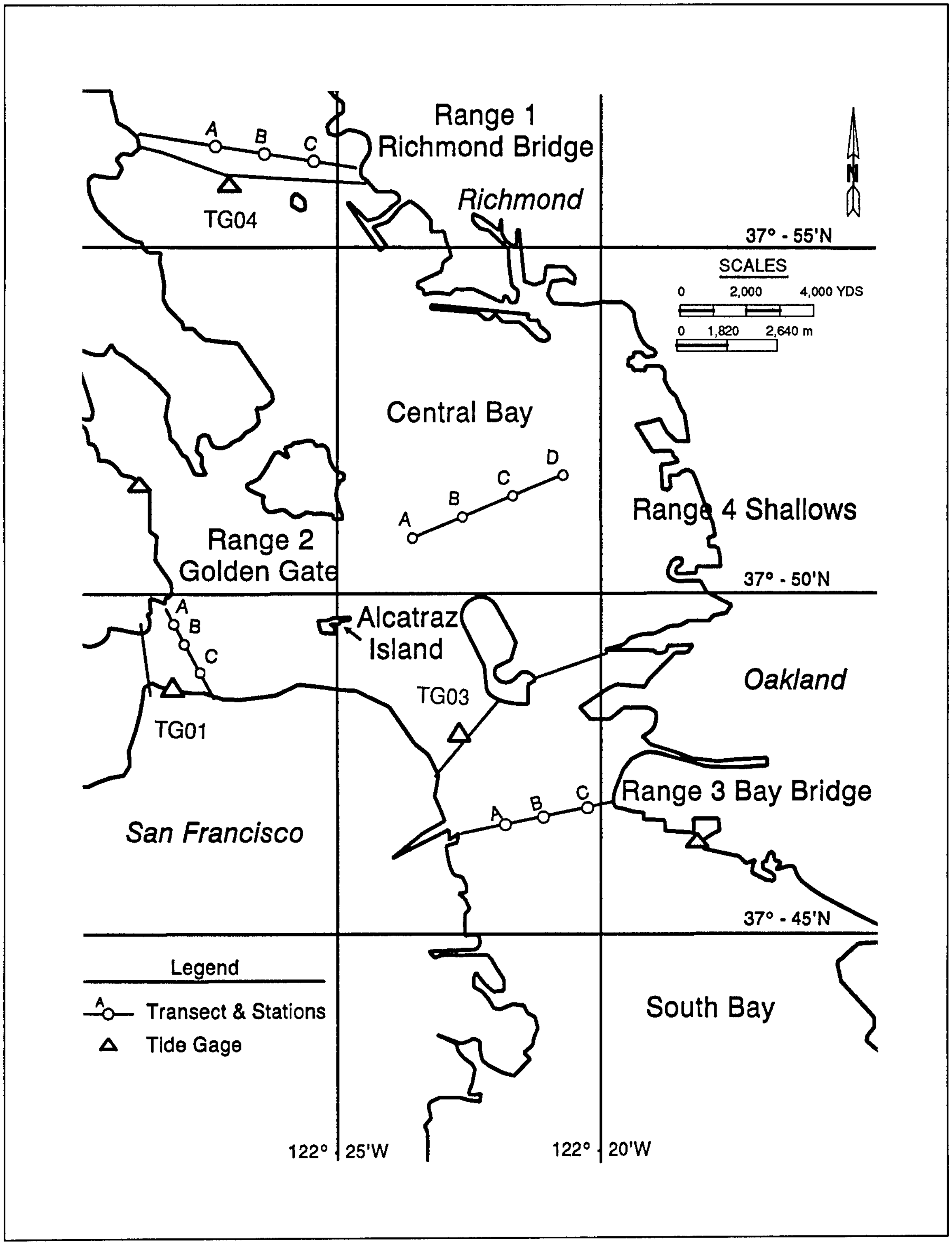


Figure 7. Sampling ranges for the 1988 survey

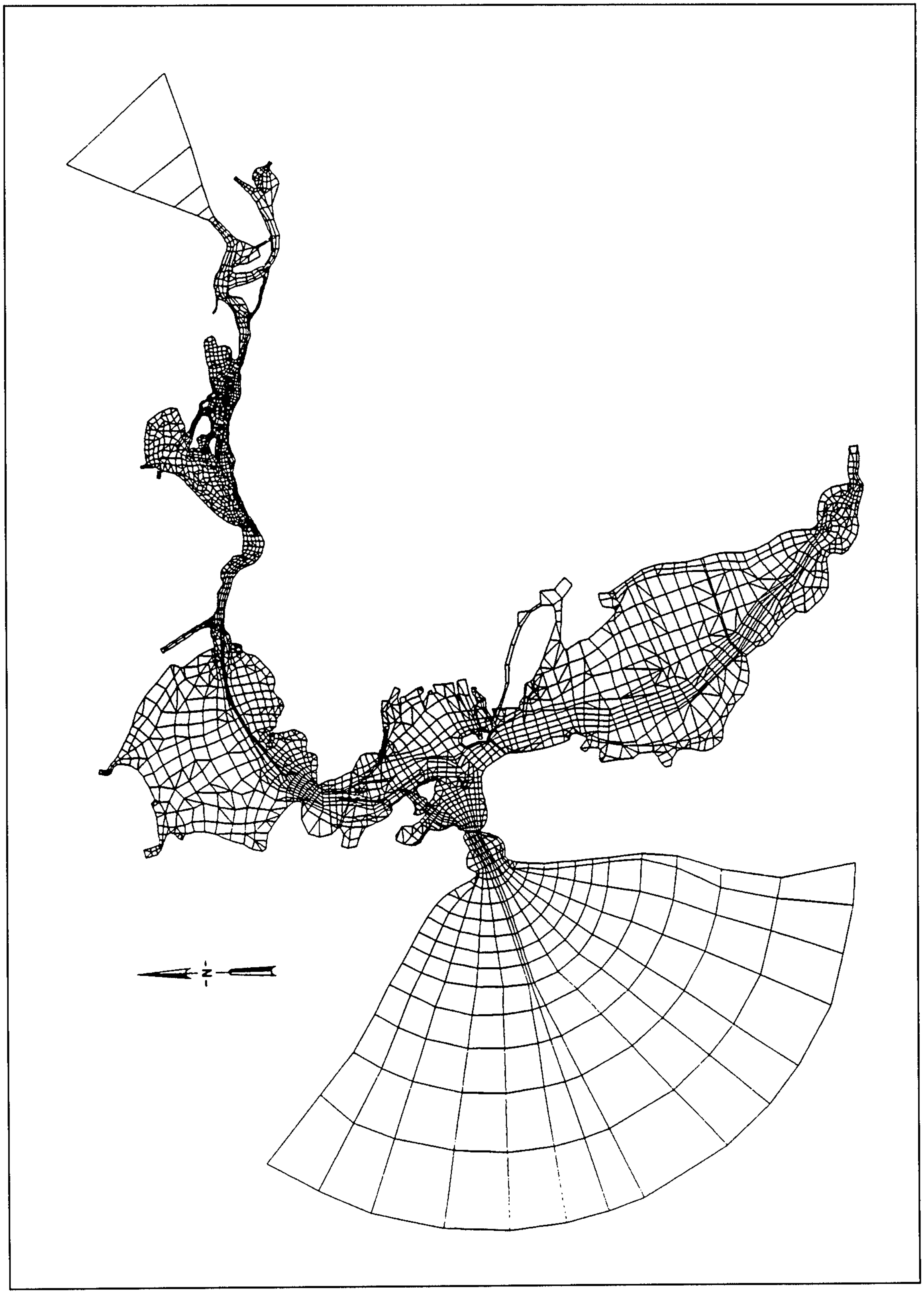


Figure 8. Complete 2-D finite element mesh used for hydrodynamic and sediment transport models

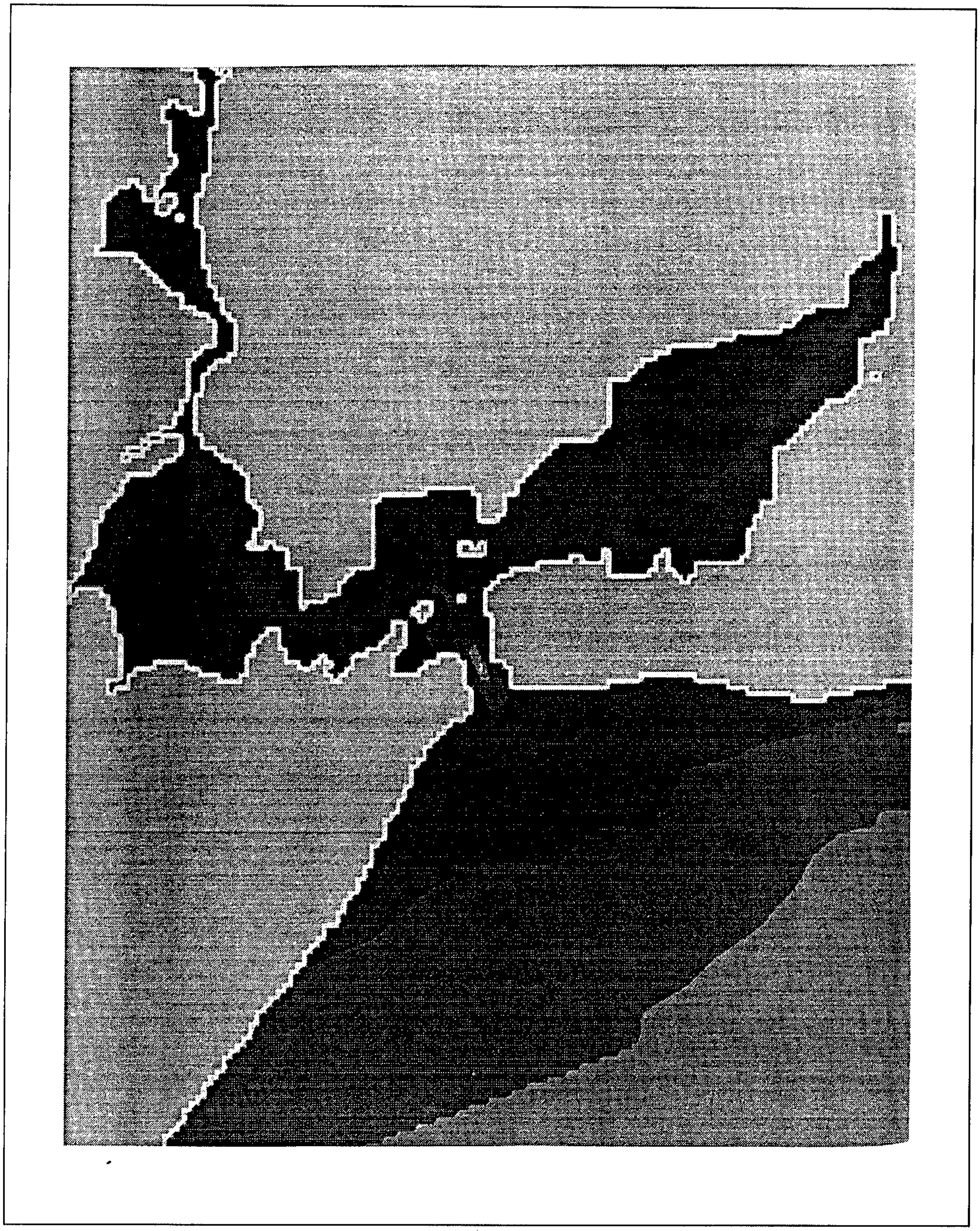


Figure 9. Grid for wind and wave models showing depth contours

The wave model formulation was developed by Dr. Resio, while the actual computational mesh for San Francisco Bay was developed by WES. The wave model solves the evolution, transport, and dissipation of the parameterized wind-generated wave energy spectrum. The wave model uses a regular finite difference grid, as shown in Figure 9, in the solution development. WES developed a model interface that provides the output to the TABS-MD finite element mesh for direct incorporation into the sediment transport model.

Sediment Transport Modeling

Two-dimensional sediment transport modeling was used for this investigation as an interim analysis in the long-term strategy leading ultimately to 3-D modeling of the system. Although portions of the system have strong 3-D processes, it is unclear to what extent the vertical variations are important for the disposal sites being considered. Therefore, the 2-D sediment transport analysis has been paired with 3-D hydrodynamic modeling to quantify 3-D influences. The evaluation of 3-D effects is presented in Report 1.

The sediment transport model used in this study was STUDH, the 2-D depth-averaged sediment transport model of the TABS-MD numerical modeling system. The model is described in Appendix A of Report 1 of this series.

Sediment Fate Analysis

The sediment fate analysis was designed to provide guidance about where in the system disposed material is likely to pass or ultimately deposit. The fate of sediment placed at dredged material disposal sites was estimated through a differencing procedure involving a background simulation without dredged material placement and a simulation with dredged material placement at some specific phase within the tidal cycle.

The differencing technique allows for isolation of the relative influence of the material placement on suspended concentrations and bed deposition patterns. From the tracking of the difference, concentration cloud impacts on sensitive migratory paths may be inferred. The differences in deposition patterns provide some indication of potential ultimate fate of placed material. The sediment fate analysis was performed using the verified sediment transport model. Because of the conditions used in the verification, only low-flow conditions were used in the sediment fate analysis, presented in Report 3.

Verification Terminology

WES has adopted an approach toward model verification that warrants a detailed discussion for clarification of the work described herein.

Several aspects of model confidence development can be addressed classically. When a model computer program is initially developed, typically a series of tests are performed to establish confidence that no glaring errors in coding are present in the model code. Such testing has been performed on all models used in this study and will not be described here. In addition, these model codes have been applied to numerous other study sites successfully, providing further confidence that the model formulation has been properly implemented in the computer codes.

A common convention applied in the scientific modeling community is that a model application first undergoes a "calibration" phase, where model coefficients are adjusted such that one data set is replicated by the model. Then a second condition is simulated using the fixed coefficients to "verify" the model. The difficulty with that approach is that if either the first or second data set has significant errors, then the model will undoubtedly fail the two-step test procedure.

A second difficulty with this approach is that if the modeler uses any information from the second data set to calibrate to the first set, the unbiased "blind" procedures are violated. When one modeler's success is compared to another's, relative adherence to the blind procedures would have an influence.

A third, and most significant, fault of a two-step model verification is that it produces a less than optimum verified model. If the two data sets are insufficiently dissimilar, a false degree of certainty is created. If the data sets are dissimilar, a better adjusted model results from iterative passes between the two sets. Finally, the two-step procedure implies that two data sets are always sufficient, whereas, in many cases three or four or more data sets are needed.

Given the uncertainty of potential data errors, WES has adopted over the past 60 years a philosophy that the best approach to obtaining proper model performance is to use all data at the modeler's disposal in a verification ensemble of tests. This approach allows for the development of model coefficients that provide the best replication to all of the data sets.

Therefore, the use of the term "verification" will imply use of all data sets in the development of model coefficients.

4 Analysis of Central Bay Suspended Sediment Field Data

The Central Bay is roughly defined as that portion of San Francisco Bay bounded by the Richmond, Oakland-Bay, and Golden Gate Bridges. The area of Central Bay between the WES measurement ranges amounts to about 205 sq km (79 square miles), and has a tidal prism of about 255 million cubic meters (9 billion cubic feet) during a mean tide. South of the Central Bay lies South Bay, to the north lies San Pablo Bay, and to the west lies the Pacific Ocean. This chapter reviews results from a 1988 WES survey to quantify sediment fluxes through Central Bay, and presents an analysis of the suspended sediment field data collected during the 1992 study. Figure 5 shows the WES sampling stations in Central Bay occupied in 1992, and Figure 7 shows the layout of sampling stations occupied in 1988.

1988 Field Measurements and Results

Field measurements were performed in September 1988 as described by Hauck et al. (1990). The freshwater outflow from the delta during this period was only about 71 cu m/sec (2,500 cfs). Dredged material disposal was moderately light; about 35,000 cu m (45,000 cu yd) were disposed at the Alcatraz disposal site during September, compared to an average of 126,000 cu m (164,000 cu yd) per month for all of 1988.

As described in the section, "Field Data Collection," in Chapter 3, a 25-hr intensive survey was performed on 7-8 September 1988. Boats repeatedly moved between stations along each of the four ranges shown in Figure 7. Hourly samples of suspended material and point measurements of current speed and direction were taken at each station. Generally, three depths were sampled in the vertical. Conductivity and temperature were measured in situ at Range 2.

Problems developed at Range 1 immobilized the sampling boat, and limited sampling to Station C. Station keeping problems occurred at Range 2 because

of deep depths and strong winds. Current measurements at Range 2 were unreliable.

In the absence of current information at Range 2, tidal total suspended material (TSM) flux was estimated by a tidal prism method. The average TSM concentrations on what were assumed to be flood and ebb tidal phases were multiplied by the estimated flood and ebb tidal volumes. Range 2 results indicated a landward TSM flux of 4,000,000 kg (4,000 metric tonnes) per lunar day.

1992 Field Data Collection

A 2-week field data collection effort was made during June 1992 to provide data for numerical model verification and boundary conditions and to allow direct estimates of suspended sediment fluxes at key ranges in Central Bay. The net freshwater outflow from the delta during May and June averaged about 100 and 110 cu m/sec (3,600 and 3,900 cfs), respectively. June had a short-duration discharge peak of 185 cu m/sec (6,500 cfs), which occurred on the third day of the month. Dredged material disposal at Alcatraz was 23,100 cu m (30,000 cu yd) for June compared to a monthly average of 167,000 cu m (217,000 cu yd) for all of 1992. Monthly disposal volumes for April and May were 682,000 and 230,000 cu m (866,000 and 299,000 cu yd), respectively.

The principal monitoring was performed from three boats, which traversed ranges taking discrete water samples and continuous acoustic transects. The data collection approach was to use acoustic methods to obtain high-resolution spatial coverage of currents and suspended sediment conditions over the transects. In addition to the survey boats, monitoring instruments also collected data in South, San Pablo, and Suisun Bays. As shown in Figure 6, water levels, salinities, and temperatures were monitored at six tide-gauge stations; current speed and direction were monitored by unattended instruments at seven locations. Wind speed and direction were recorded at Alcatraz Island. Bottom samples were collected at 158 sites. Further details are provided in Report 4.

Instrumentation and Sampling

Direct-reading ADCP's were mounted on three boats of 14- to 16-m (45- to 52-ft) length. These instruments were leased and set up onboard by the manufacturer, RD Instruments of San Diego, CA. The unit used at Range 2 used 150-kHz broadband frequency, while the other two units were 1,200 kHz narrow band.

The ADCP operates by transmitting acoustic pulses from four transducers each oriented 0.35 radian (20 deg) from the vertical at 1.57-radian (90-deg)

intervals in the horizontal plane as depicted in Figure 10. The received signals are gated to resolve up to 128 depth increments. The 150- and 1,200-kHz units were configured to have 2- and 1-m-depth increments, respectively. The Doppler principle is applied to resolve current components from the frequencies of the backscattered acoustic signals. ADCP's acquire data in ensembles. Ensembles are packets of information representing the data for the entire water column at a particular distance along the transect line. Each ensemble contains the north, east, and vertical velocity components along with the acoustic backscatter for each acoustic beam on the transducer. Backscatter intensity was further processed, external to the ADCP, to resolve suspended sediment profiles. The general technique of relating backscatter intensity to suspended concentration is described by Thevenot, Prickett, and Kraus (1992). WES has used ADCP's to monitor several dredged material disposal operations although the technique is still relatively new.

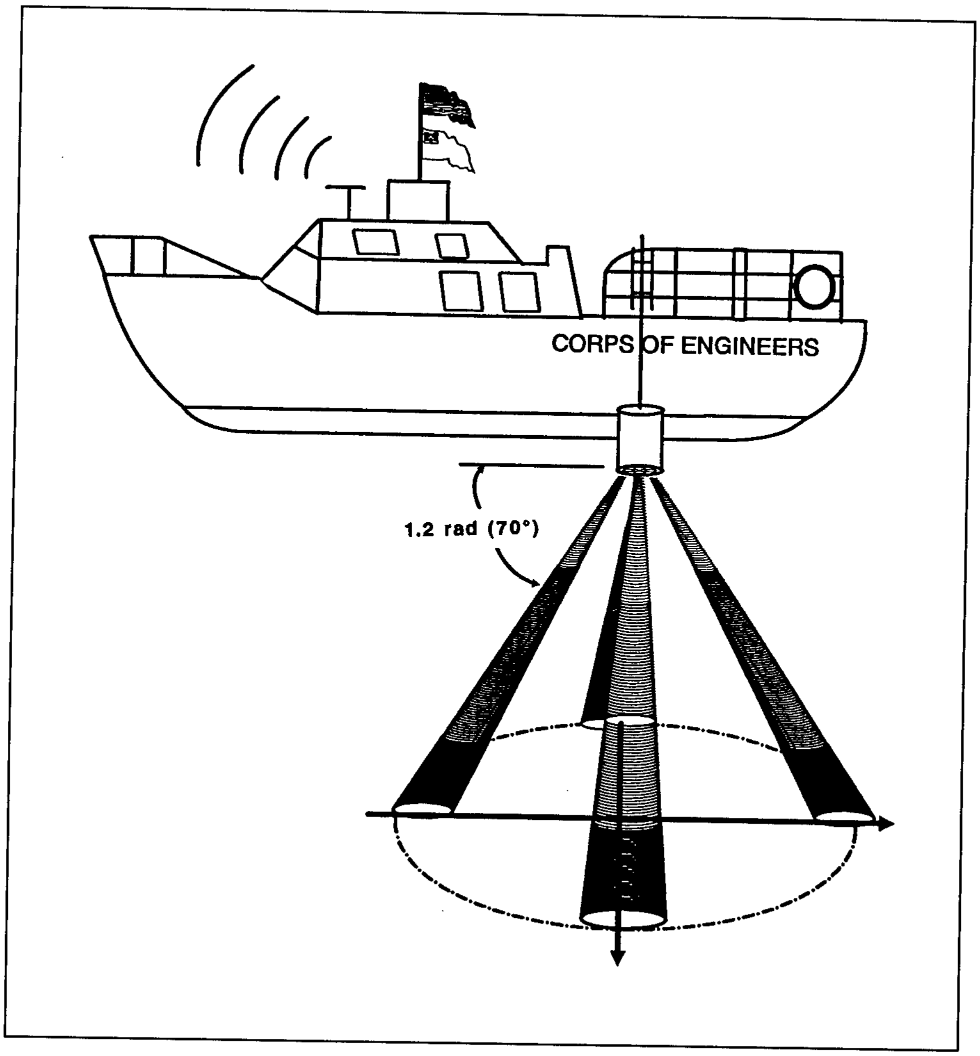


Figure 10. Configuration of ADCP beams

Suspended sediment samples collected at 25 locations along the ranges (five depth locations at five stations) were analyzed for TSM and used to make the required ADCP backscatter correlation described in the next section. Water samples were collected by water bottle sampler at Range 2 and by pump sampler at the other ranges. Water samples were kept cold and transported to WES by refrigerated truck. Laboratory analyses for TSM were carried out within approximately one week following arrival at WES. Polycarbonate, 0.45-micron pore-size filters were used for gravimetric analysis. Salinities were also measured on water samples. Particle size distributions were electronically measured on select samples from surface, middepth, and bottom depths at Station C of Ranges 2, 3, and 5.

Data Processing

Raw ADCP files were first spatially averaged for approximately each 10-m length along transects. Typically, five data ensembles were averaged together in this process. The bottom depth as located by the ADCP was identified, and any readings within one depth increment of the bed or below were rejected. Any reading for a depth interval flagged as spurious by the ADCP was also rejected. Erroneous data including duplicate readings and a small number of spurious velocity readings were rejected.

ADCP data were spatially smoothed to improve resolution of large-scale distributions. Variability in the acoustic data was believed to be caused by boat motion and turbulence in the flow field. Figure 11, a plot of the east-west velocity component for 9.5-m depth across Range 2, is an example of rapid fluctuations in velocity that were not resolved by the 6- to 8-sec averaging. A locally weighted regression fit was used to smooth data horizontally and vertically in space, as seen in Figure 11 for the horizontal dimension. Following smoothing, data were gridded to 60-m-wide by 1-m-deep cells for contouring, as well as depth and cross-sectional averaging. The same procedure was used for other velocity components and acoustic backscatter intensity.

Acoustic backscatter intensity was correlated to TSM concentrations by fitting the empirical equation:

$$\log (\mathrm{TSM}) = K + a\,Sv \tag{1}$$

where Sv is the backscatter intensity normalized by the scattering volume, and a and K are empirical coefficients. Since a and K have been found to depend on particle size in laboratory calibrations (Thevenot, Prickett, and Kraus 1992), each acoustic transect was individually calibrated using the set of TSM samples collected closest in time, usually about 45 min. The distributions of acoustic backscatter intensity and TSM concentration closest in time were used to develop regression coefficients. An example of an individual regression is given in Figure 12. A different set of coefficients was used to calculate

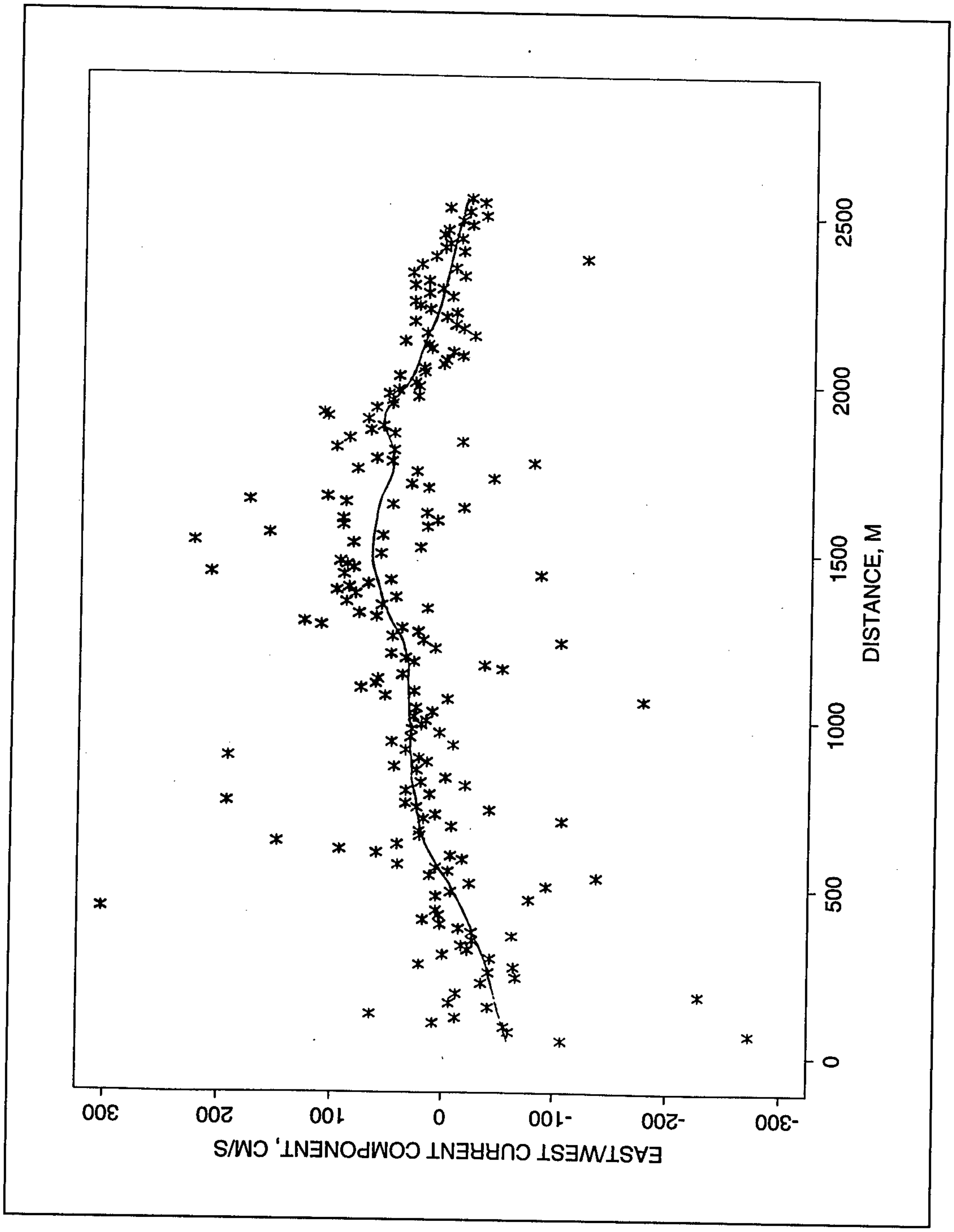


Figure 11. Examples of discrete velocity values and a smooth fit line for 9.5-m depth on Range 2

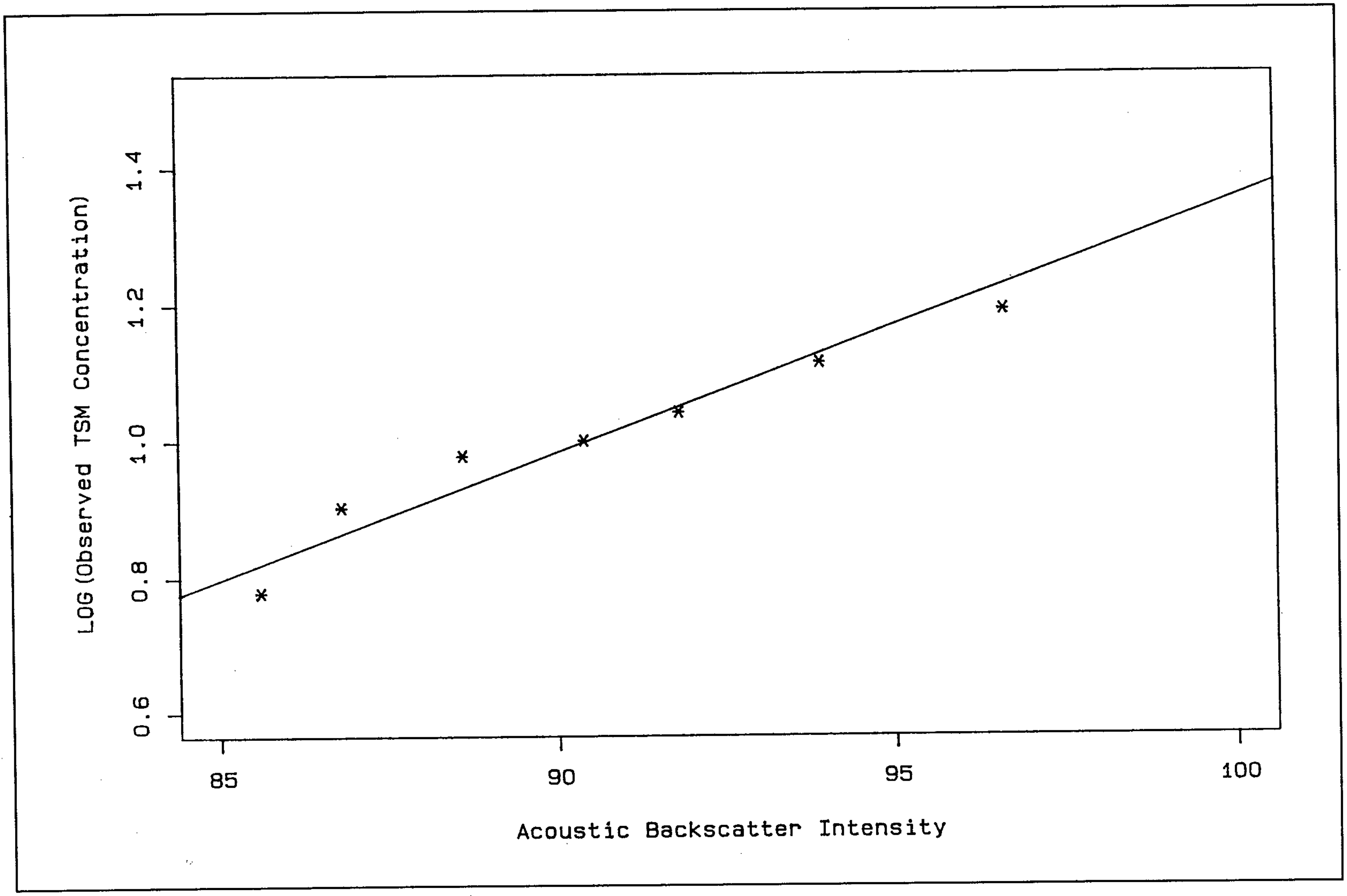


Figure 12. Example regression line for observed TSM versus acoustic backscatter intensity at a Range 2 transect

correlated concentrations for each transect according to regression results. Example backscatter intensity, correlated concentration contour plots, and discrete sample data are shown in Figures 13-15, respectively.

Range 2 data were used in additional analyses to determine the flux of TSM (in kg or metric tonnes) over tidal cycles in a neap-spring-neap sequence. First, water level and transect discharge data were used to produce a continuous discharge record at 10-min time intervals. Second, an empirical relationship between tidal discharge and tidal flux of TSM was used to calculate TSM flux from the discharge record. The TSM flux record was then integrated over a 14-day neap-spring-neap tidal sequence to obtain a representative long-term average flux for the Golden Gate range. The following paragraphs give further details of this analysis.

An empirical fit was made between measured discharges and available water level data. Under steady-flow conditions, discharge can be related to the slope of the water surface, flow depth, and spatial gradients of flow velocity. However, under tidal conditions no theoretical discharge formulation is available relating discharge to water-surface slope, etc.; therefore, an empirical approach was employed. Water level data taken at 10-min time intervals at recorder locations TGO1 and TGO3 (Figure 5) were used for this analysis. The water-surface slope between the stations was taken as the difference between water level values with their respective means removed. A time lag in the peak slopes compared to the peak discharges was observed and estimated from the data. The time derivative of the water levels at TGO1 was calculated by backward differencing the 10-min values. A multiple linear regression was performed using 84 discharge measurements as the dependent variable and slope, time-lagged slope, square root of the slope, and the time rate of water level change as four independent variables.

Corresponding values of tidal discharge and tidal flux of TSM were examined to identify their relationship. Locally weighted (nonlinear) and linear regressions were performed on the data. A relationship was sought with which to calculate or convert discharge into TSM flux.

Results

The procedure used to correlate acoustic backscatter intensity to TSM resulted in correlated concentration fields that had medians and other statistical central tendencies similar to the observed TSM transects. Figure 16 shows the 588 observed TSM values with the corresponding correlated TSM values from acoustics. The regressions between observed TSM and ADCP backscatter intensity resulted in less variation in regression coefficients than expected. A summary of the regression and correlation coefficients obtained

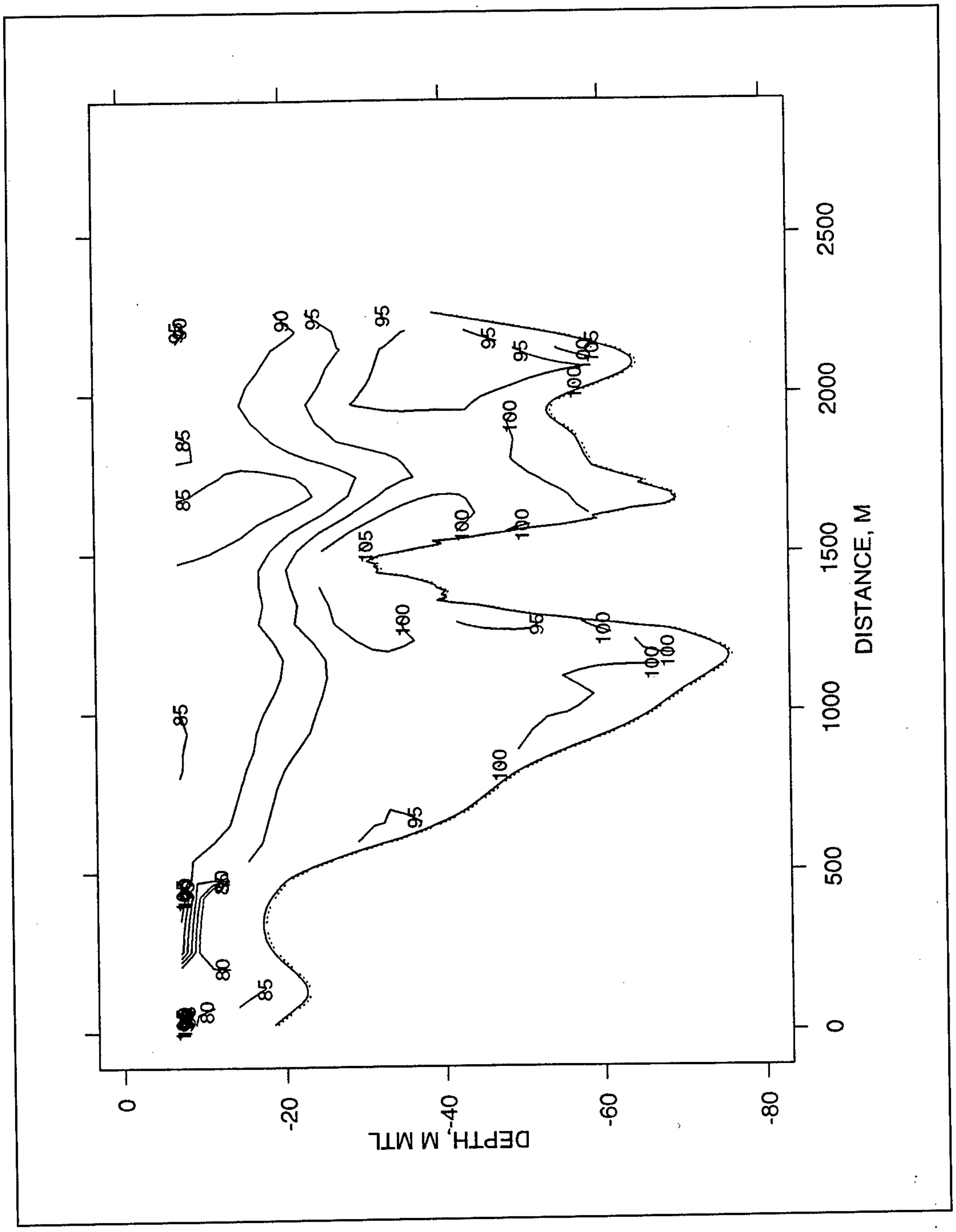


Figure 13. Example acoustic backscatter intensity transect for Range 2 taken 0700 June 9

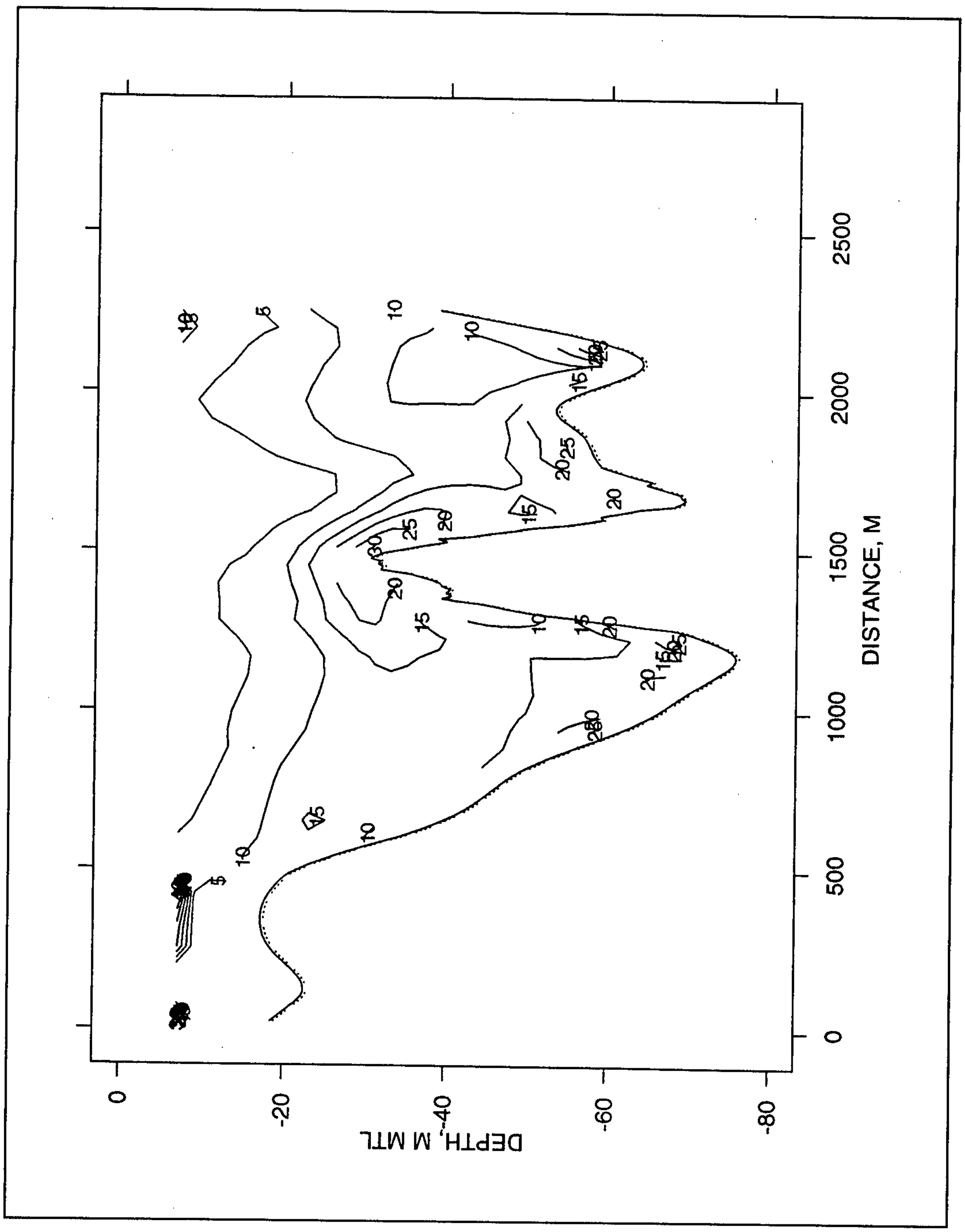


Figure 14. Example correlated TSM, mg/ℓ, for Range 2 taken 0700 June 9

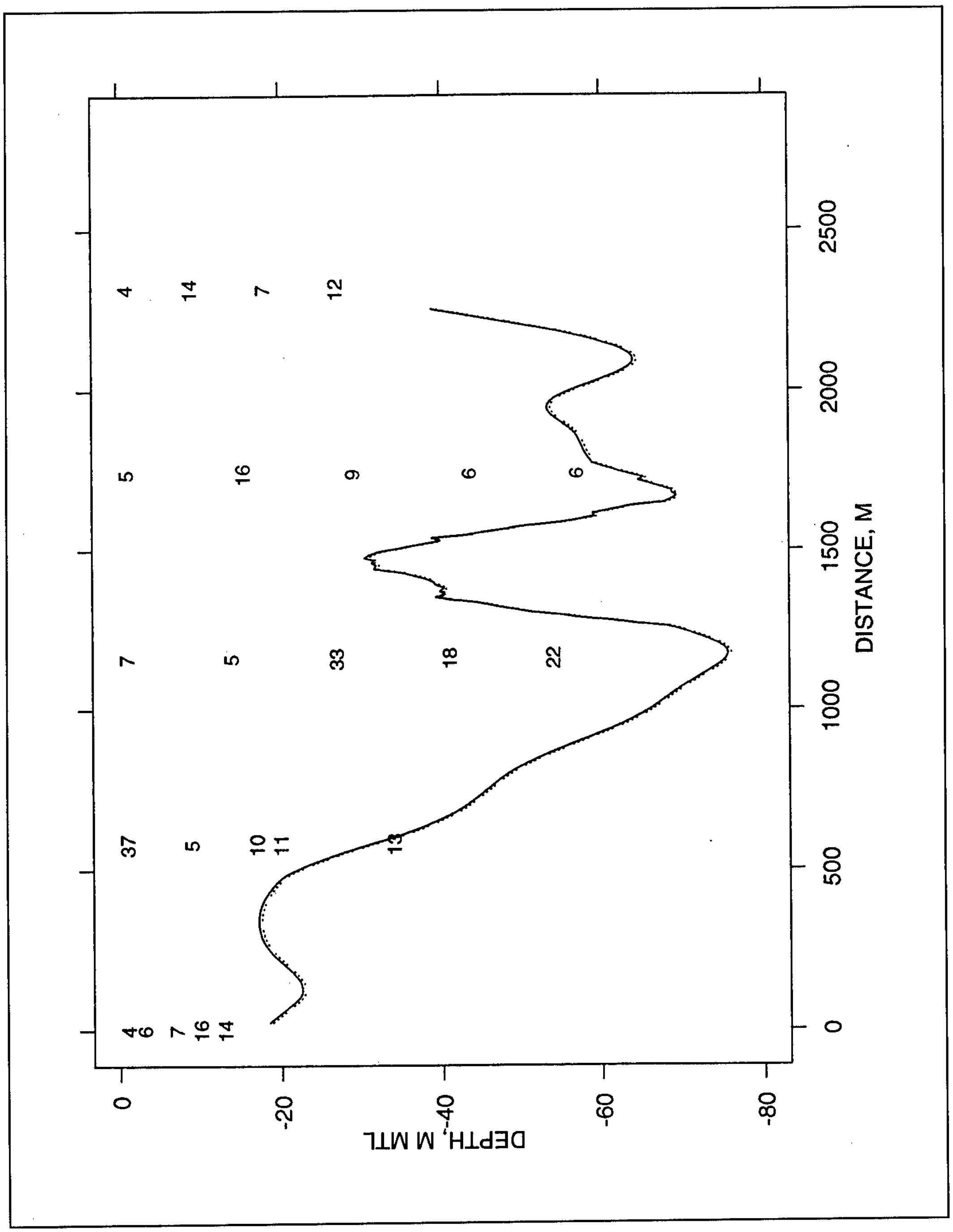


Figure 15. Observed TSM, mg/ℓ, for Range 2 taken 0730 June 9

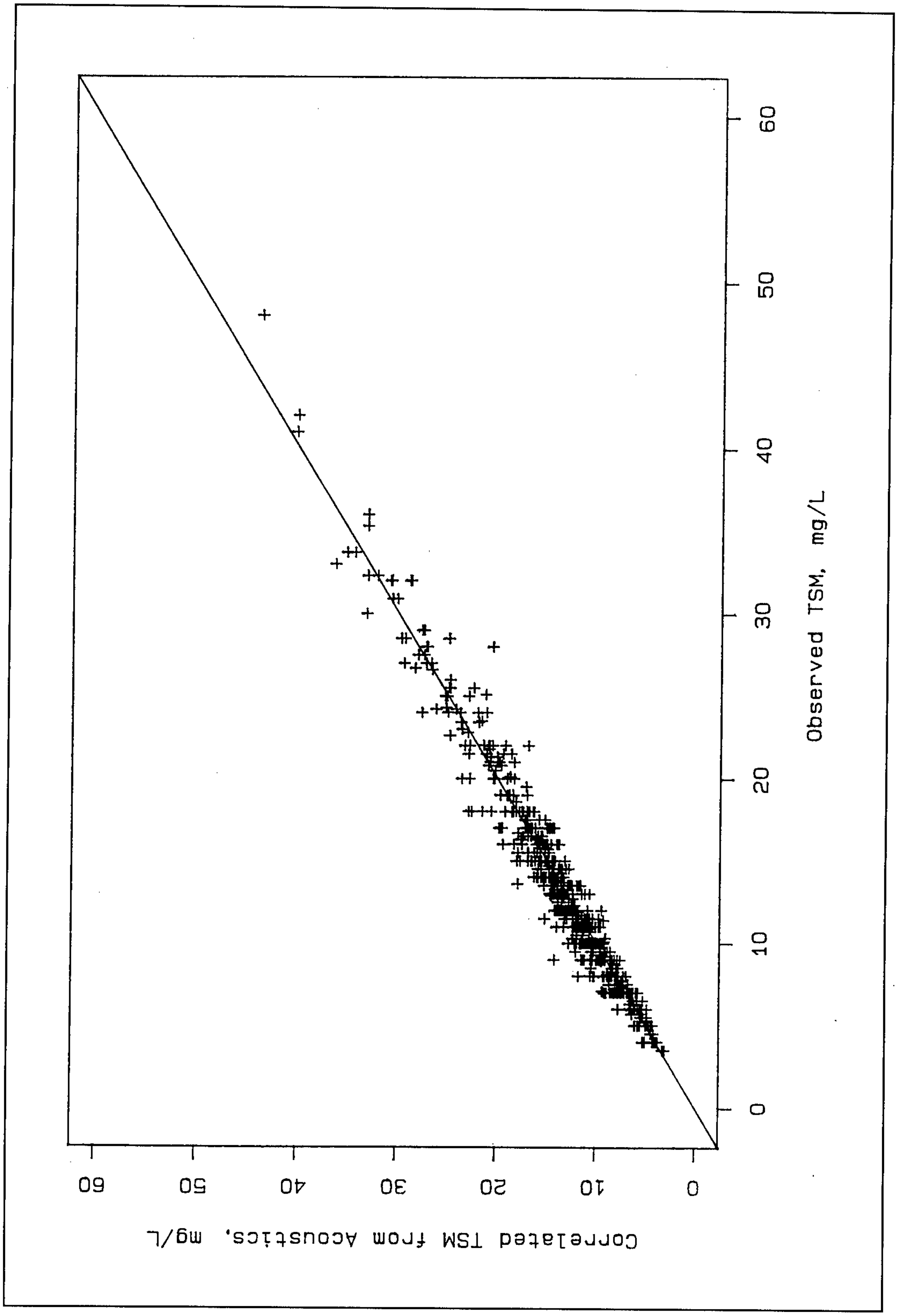


Figure 16. Scatter plot of all 588 observed versus correlated TSM concentrations for Range 2

for the 84 ADCP transects made at Range 2 is presented in the following tabulation:

Coefficient	Mean	Median	25th Percentile	75th Percentile
K	-3.193	-2.790	-3.887	-2.070
a	0.0443	0.0405	0.0321	0.0502
R^2	0.928	0.941	0.890	0.964
Note: R^2 = correlation coefficient.				

The ADCP backscatter intensity transects resulted in TSM information not possible from conventional water sampling. Figure 17 shows a comparison of transect-averaged TSM from 25 discrete observations and the corresponding correlated TSM averaged over about 770 ADCP transect cells. The continuous transects revealed several interesting features of the TSM field including high-concentration zones consistent with ebb flow through Raccoon Strait and flood flow near the center of the transect.

Different relationships between discharge and sediment flux were found for flood and ebb tidal phases. A piecewise linear relationship over certain discharge ranges was suggested by the locally weighted (nonlinear) and linear regressions performed. A simplified linear relation was constructed to cover these ranges. These relationships are shown in Figure 18, and the break in the ebb-phase relationship should be noted. These relationships were used to calculate or convert the discharge sequence into a sequence of TSM fluxes. TSM fluxes, times the time interval (10 min), were accumulated to obtain the total flux over the 14-day period as described later.

Figure 19 shows tidal discharge, TSM flux, and flux-weighted average TSM values for the ADCP transects taken across Range 2 (Golden Gate) and the tidal elevation record from TGO1. Figure 20 shows instantaneous and smoothed values of water level slope and time rate of change in water-surface elevation, and discharge measurements and synthesized discharge sequence. The correlation coefficient R^2 was 0.97 and the standard error of the residuals was 13.9 thousand cubic meters per sec (kcms). Using the regression results and the water level records, a sediment discharge sequence was synthesized for a 14-day neap-spring-neap time period between 8 and 22 June 1992. Figure 21 shows observed and synthesized instantaneous TSM fluxes for the 14-day neap-spring-neap tidal sequence. The standard deviation of the residuals between the ADCP estimated TSM fluxes and the synthesized values was 300 kg/sec (0.30 metric tonne/sec) and the median residual was -40 kg/sec (-0.04 metric tonne/sec). Positive transport is landward and negative transport is seaward.

Figure 22 shows the cumulative flux over the same neap-spring cycle. The cumulative net flux for the 14 lunar days (28 flood tides and 28 ebb tides) was

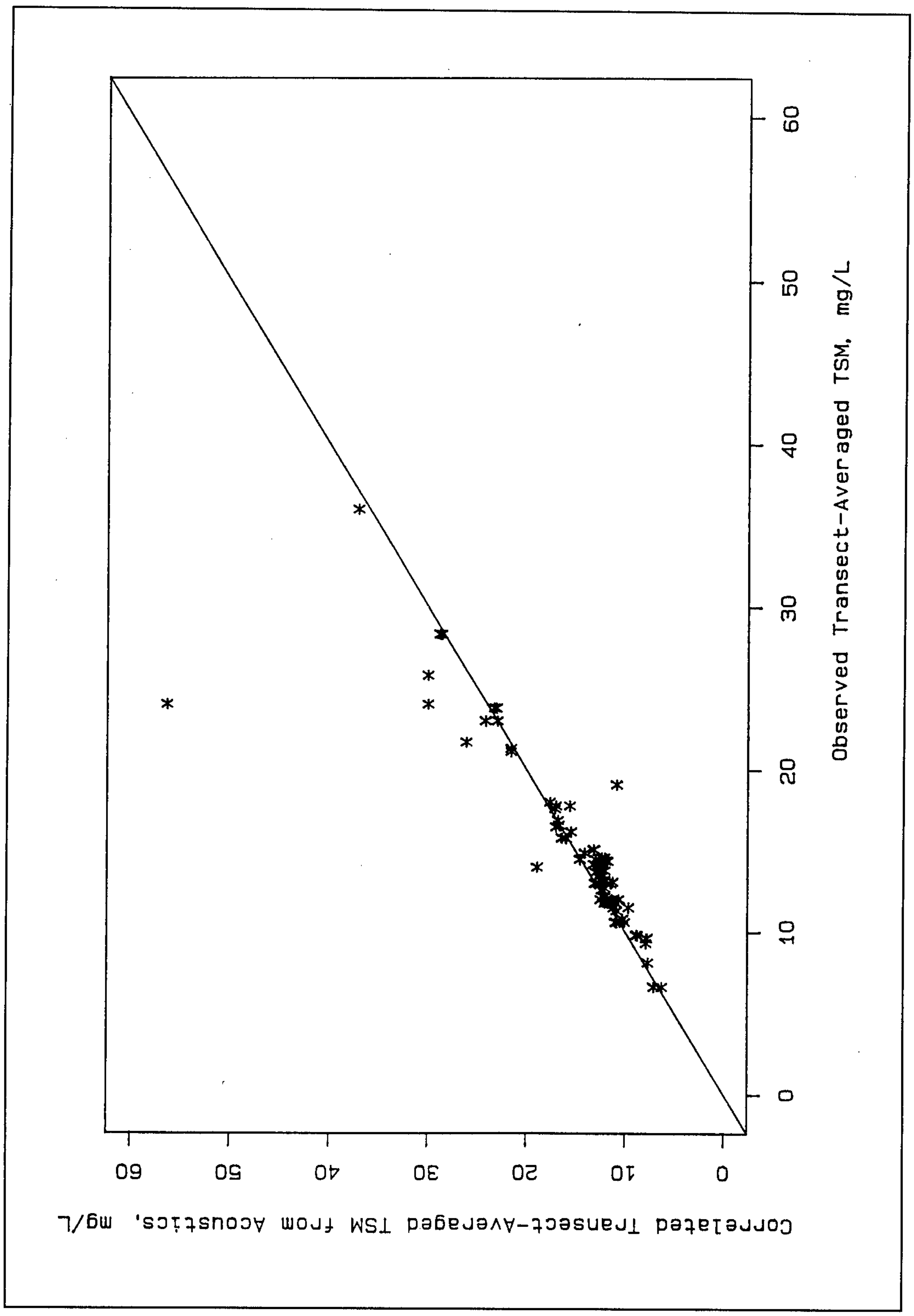


Figure 17. Scatter plot of 94 transect-averaged observed versus correlated TSM concentrations for Range 2

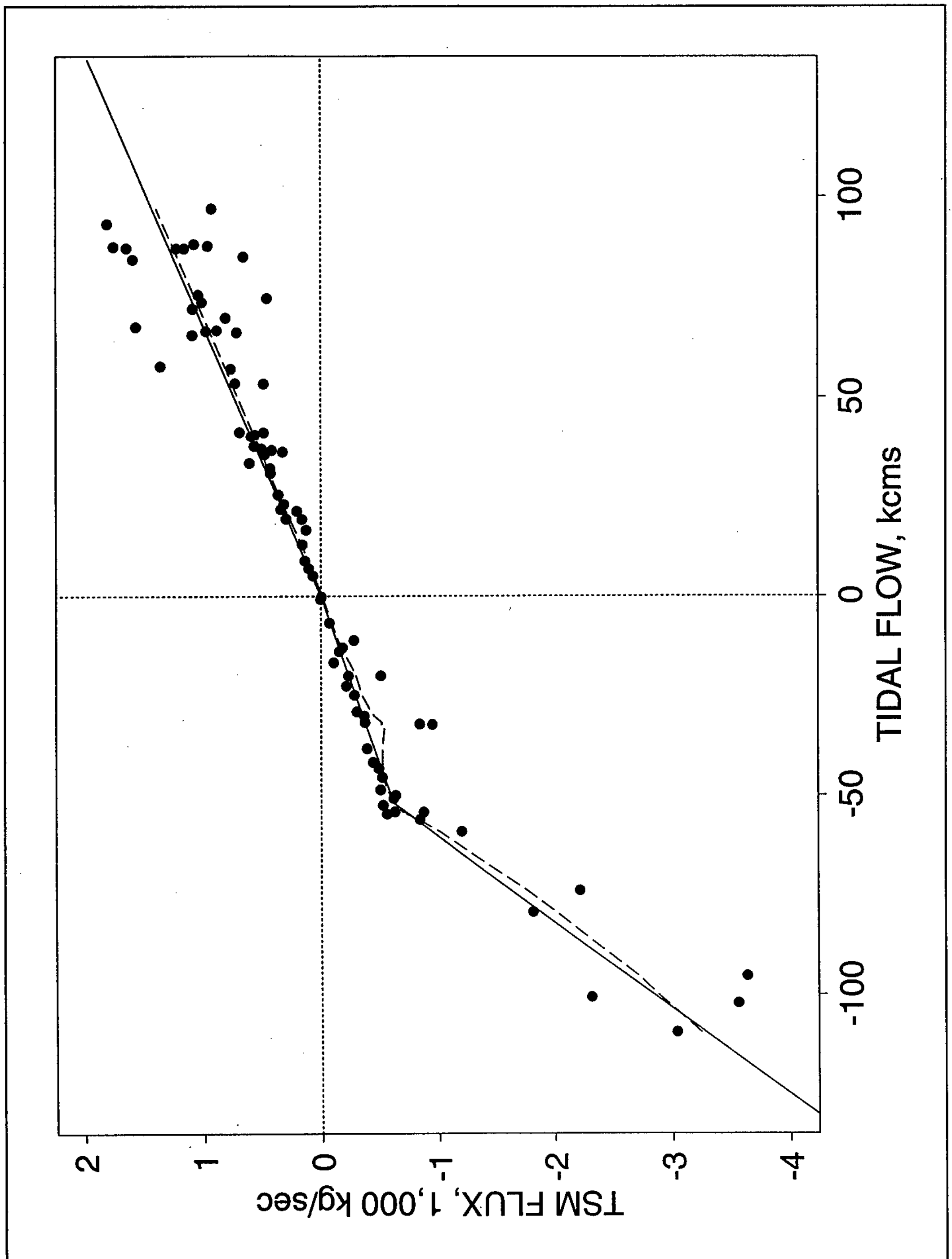


Figure 18. Range 2 tidal flow and TSM flux data with nonlinear regression and piecewise linear relationships

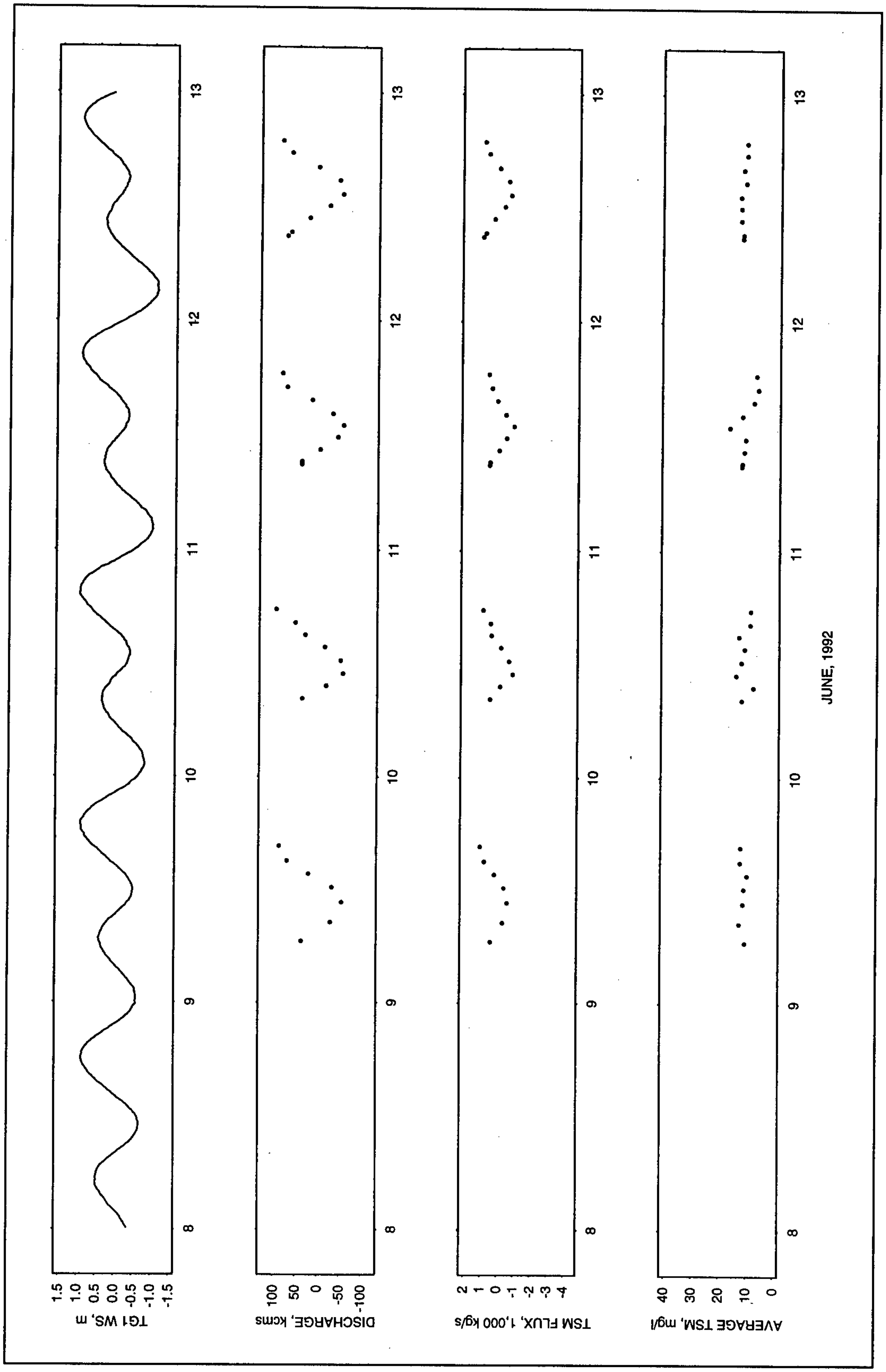


Figure 19. Range 2 ADCP flow and TSM flux results (Sheet 1 of 3)

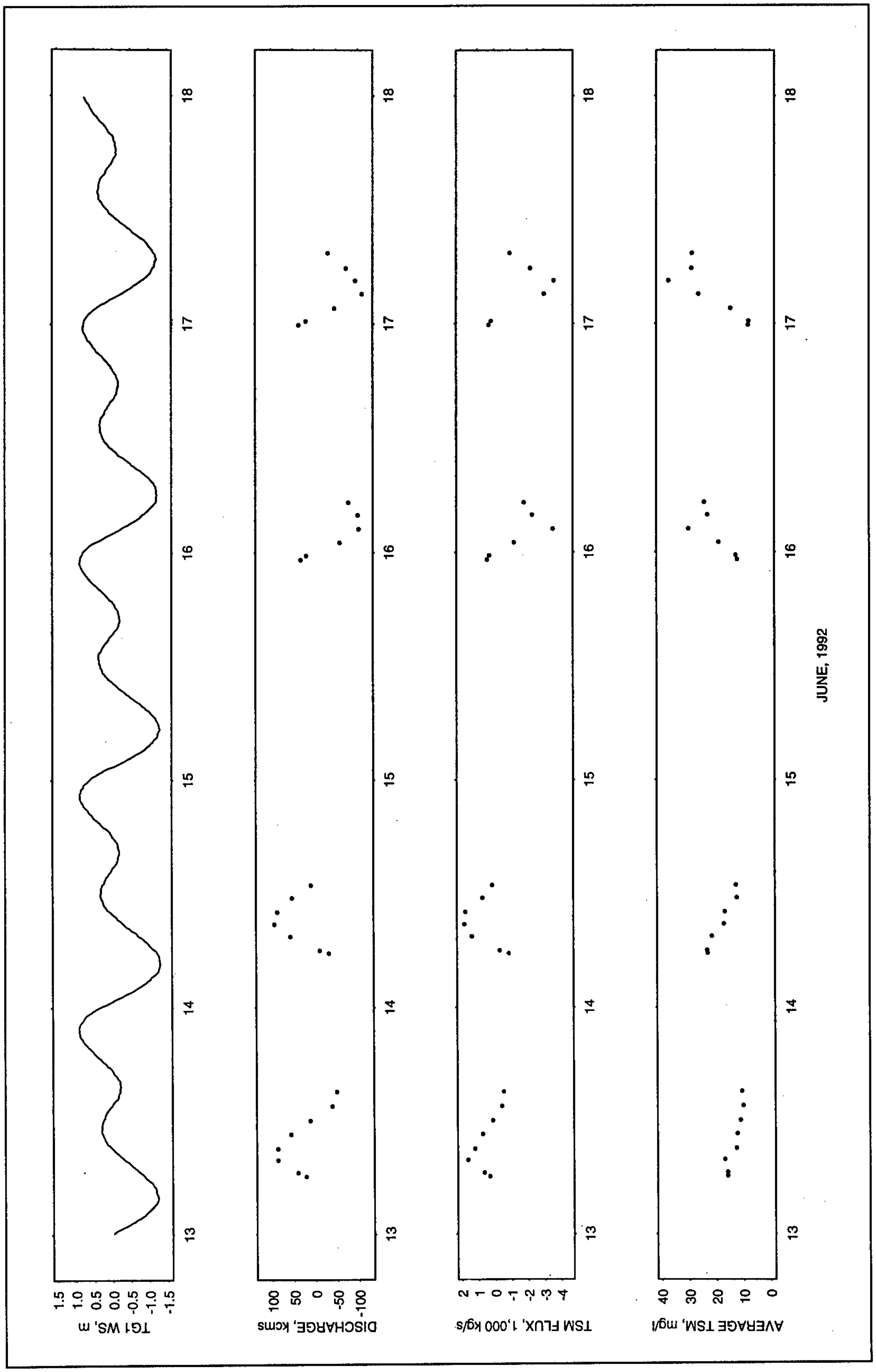


Figure 19. (Sheet 2 of 3)

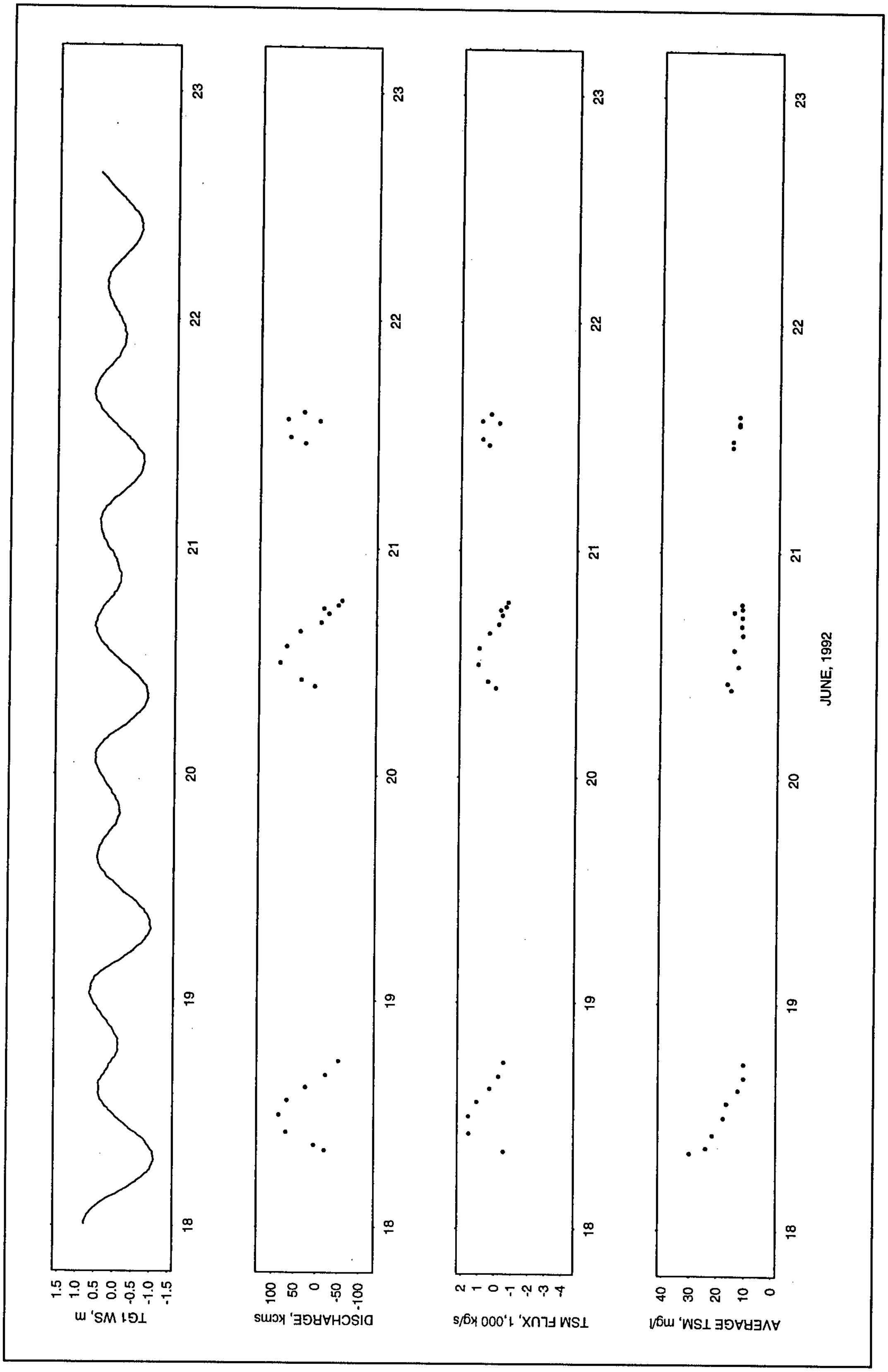


Figure 19. (Sheet 3 of 3)

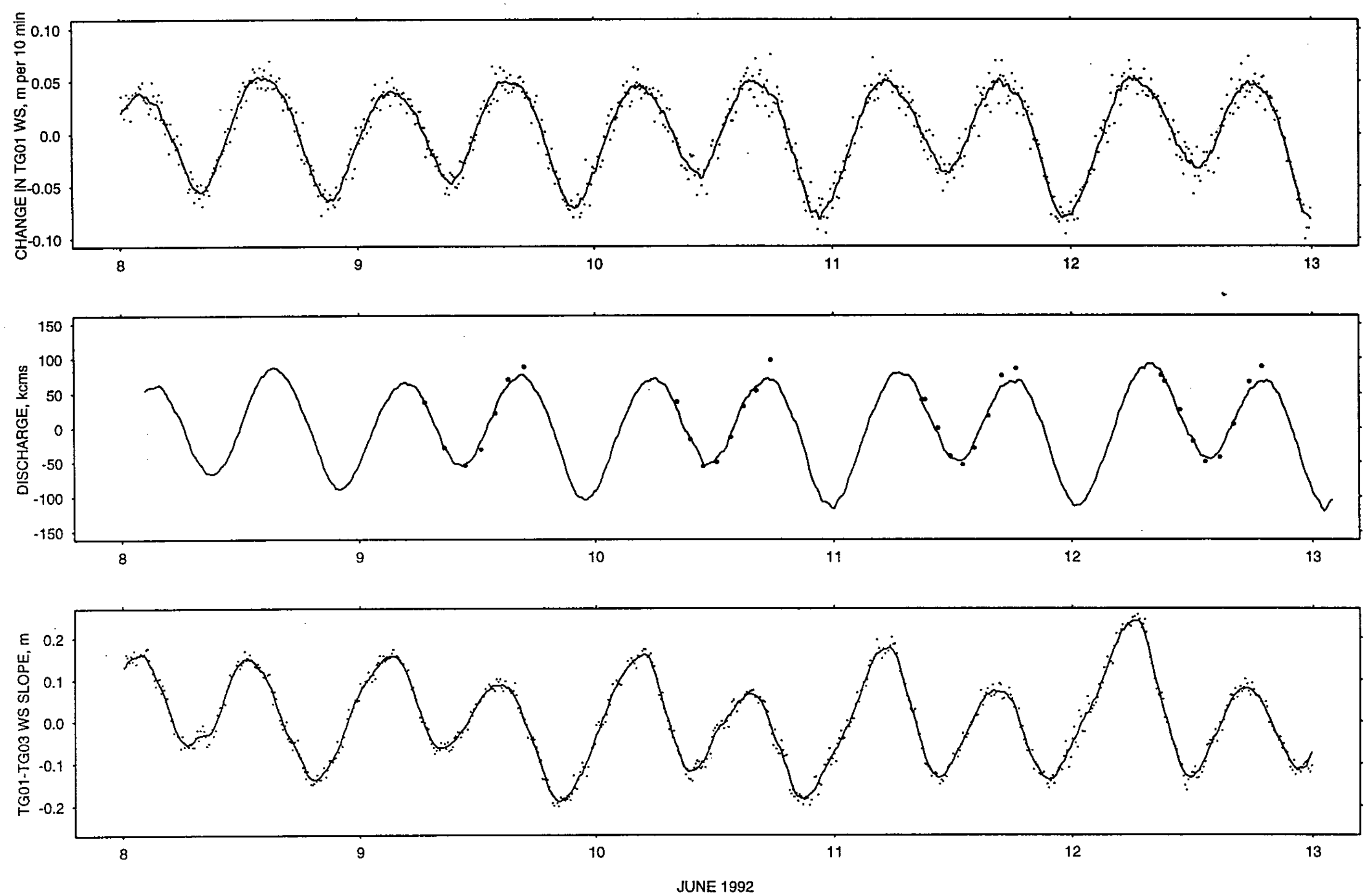


Figure 20. Instantaneous and smoothed time change in water level (top) and water-surface slope (bottom), and discharge measurements (•) and synthesized discharge sequence (middle) (Sheet 1 of 3)

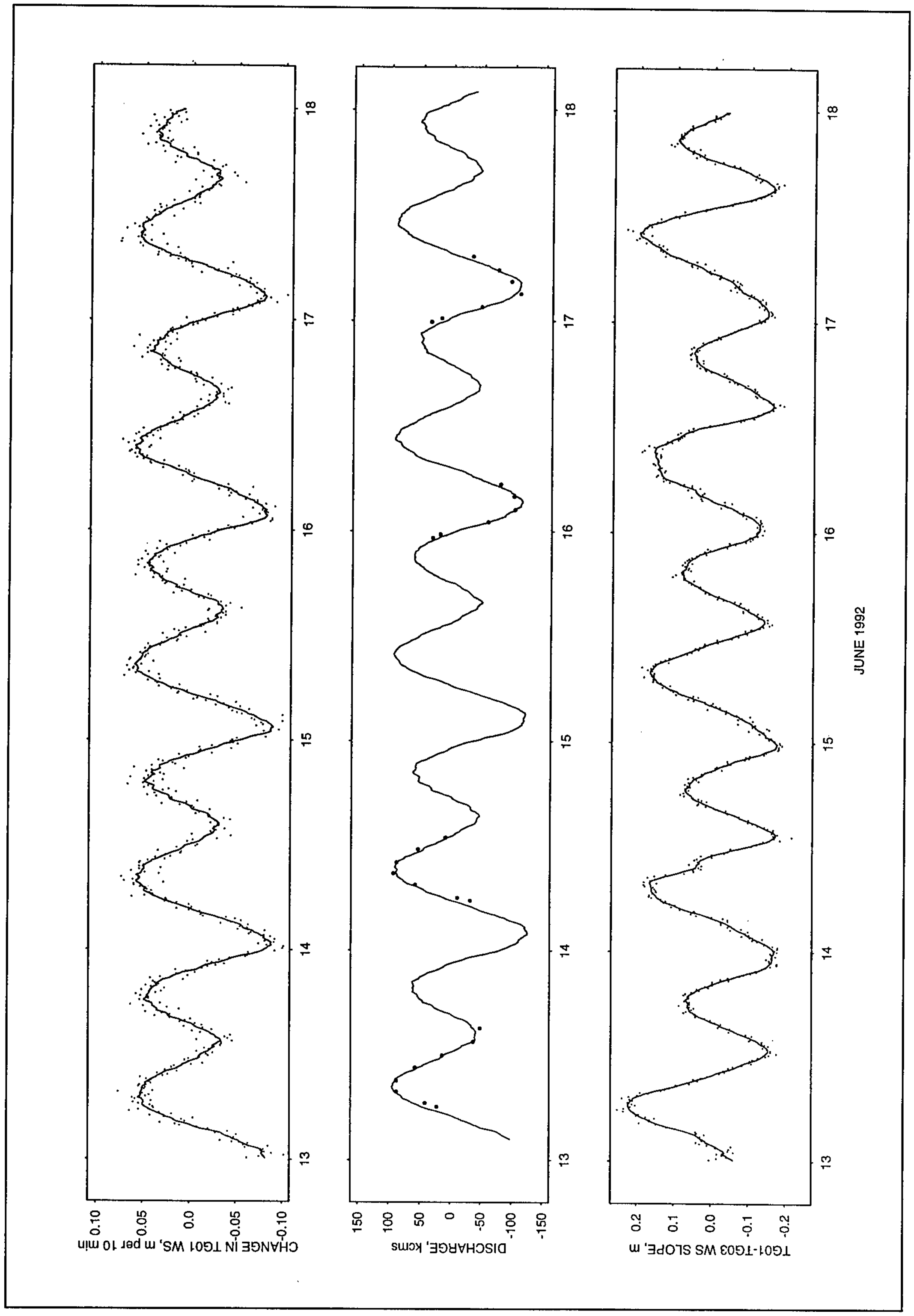


Figure 20. (Sheet 2 of 3)

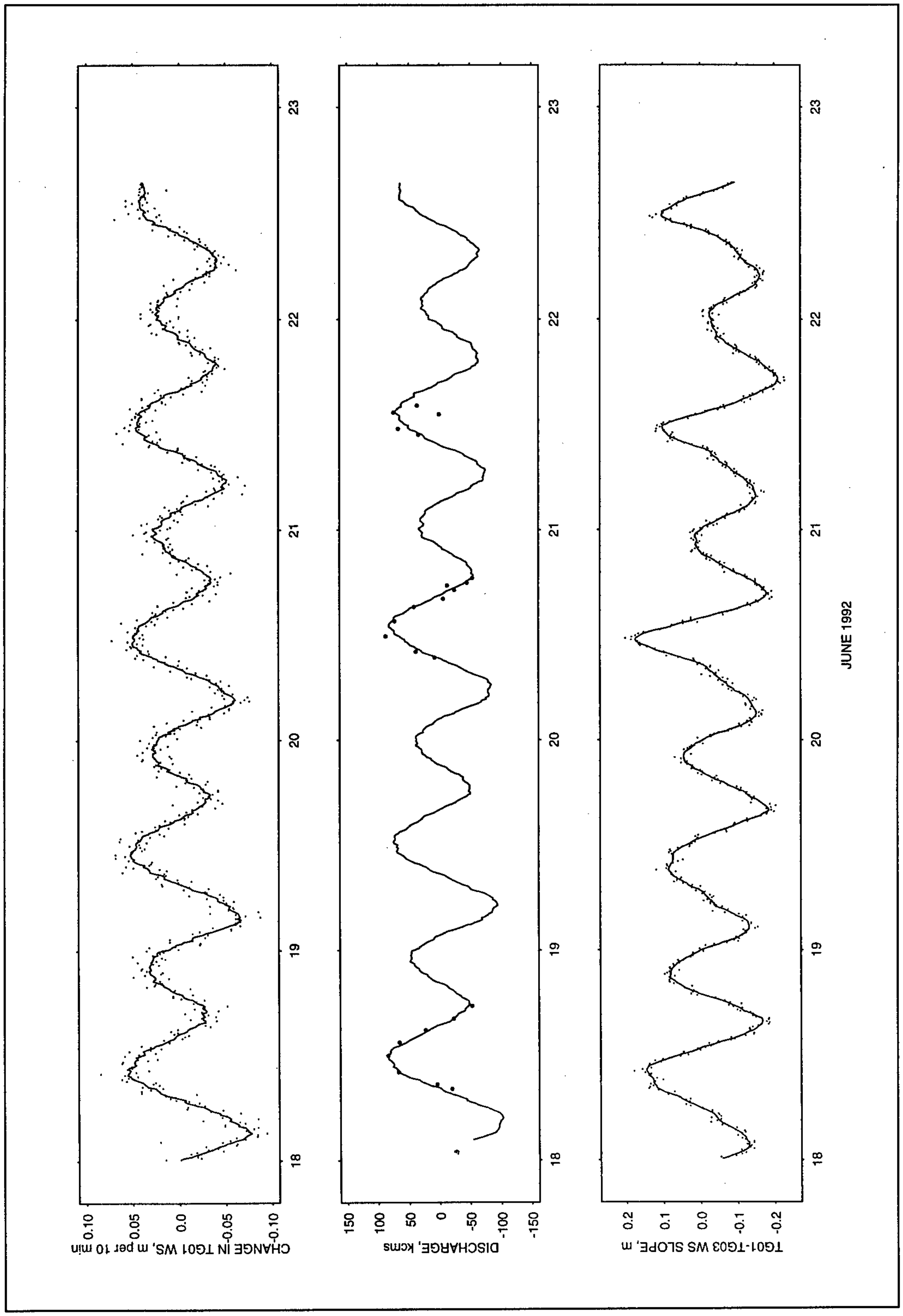


Figure 20. (Sheet 3 of 3)

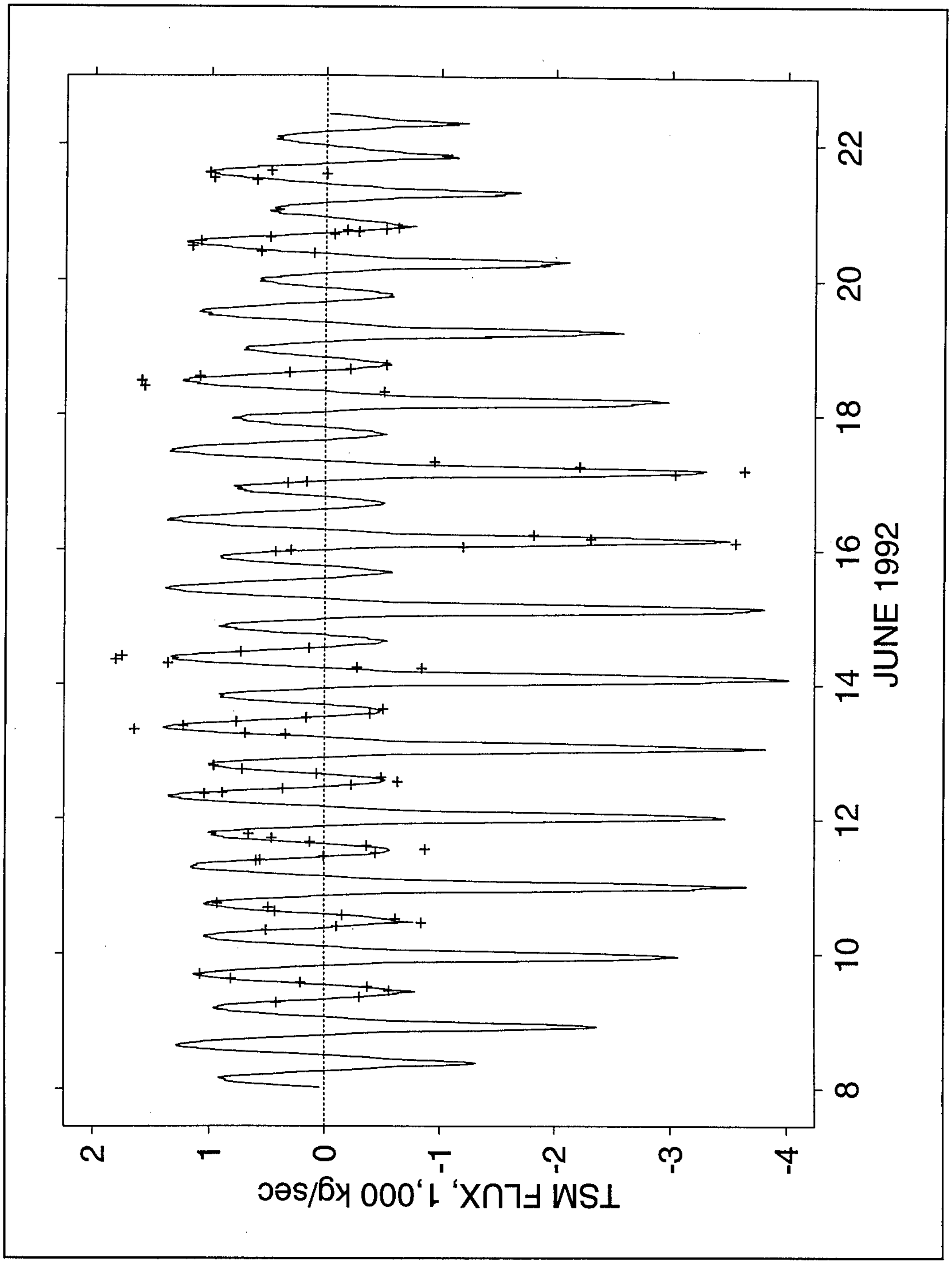


Figure 21. Observed and synthesized TSM flux at Range 2 for neap-spring cycle

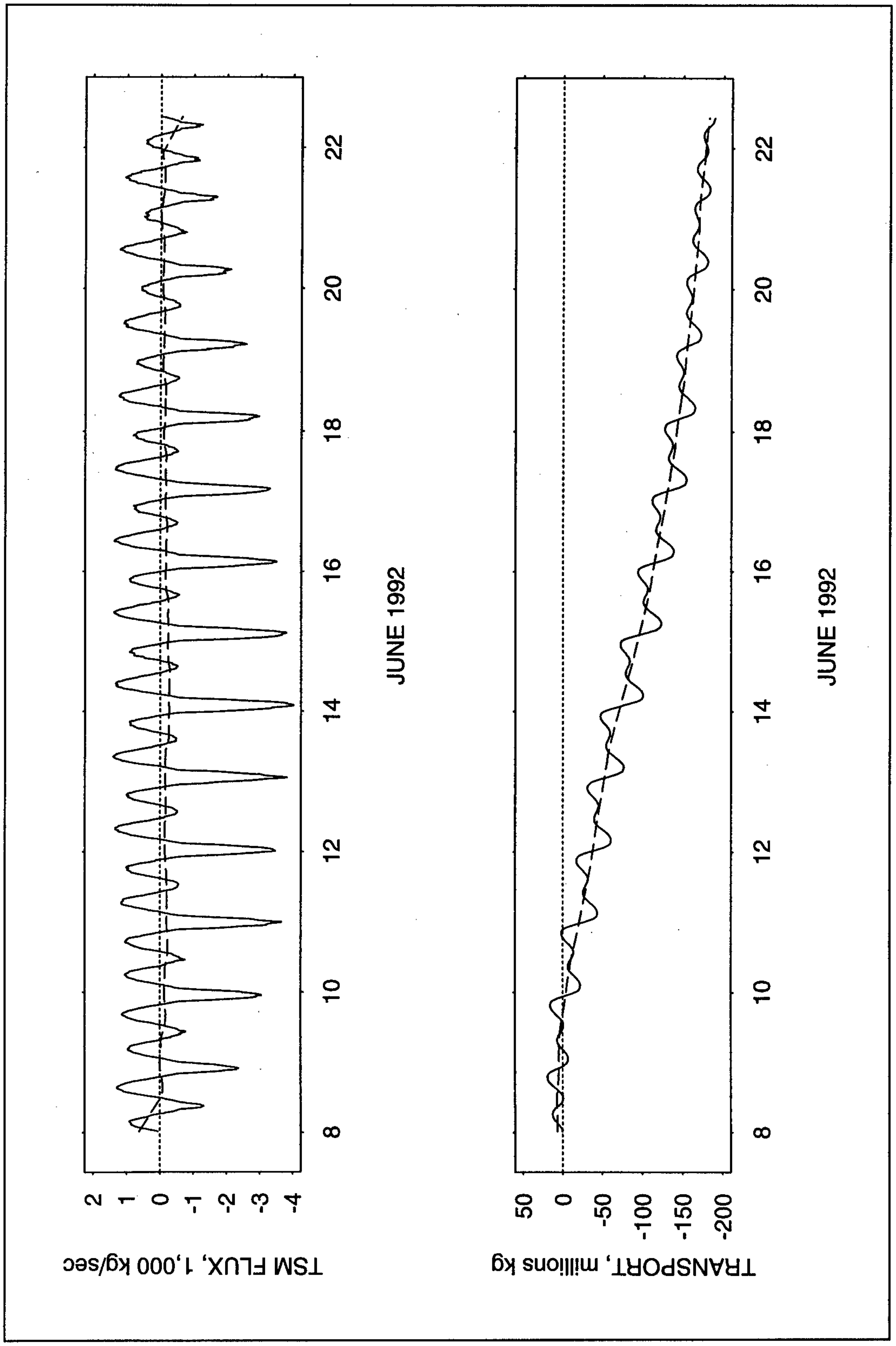


Figure 22. Synthesized instantaneous (top) flux TSM and cumulative TSM transport (bottom) with tidal-average trend line (dashed)

-188×10^6 kg (-188,000 metric tonnes). This amounts to an average of -13.4 $\times 10^6$ kg (-13,400 metric tonnes) per lunar day over the neap-spring cycle. Total flood TSM flux was 425×10^6 kg (425,000 metric tonnes), and the total ebb flux was -613×10^6 kg (-613,000 metric tonnes). Therefore, the ebb tide TSM fluxes were on average 1.44 times as great as the flood tide fluxes. However, there was a pronounced inequity between the two daily ebb fluxes as shown in Figures 21 and 22. The stronger ebbs had maximum instantaneous fluxes more than twice corresponding flood levels.

Discussion

The LTMS sediment budget study arrived at an estimate of sediment export from San Francisco Bay of 2.59 million cubic meters (3.37 million cubic yards) per year for the period 1955-1990, compared to a sediment inflow of 6.07 million cubic meters (7.88 million cubic yards) per year (Ogden Beeman and Associates, Inc., 1992). That study compared sediment inflows, removal of sediment to upland disposal, and measured accumulation of sediment in the system, and assumed that the missing material was exported from the system through the Golden Gate. The present study confirmed that exports of such magnitude might occur. The analysis of ADCP and related data indicates that the sediment outflow from San Francisco Bay occurred predominantly on the strong ebb phases, was greatest during spring tides, and amounted to approximately 188,000,000 kilograms (188,000 metric tonnes) over the 14-lunar-day period. That compares to 53,100,000 kilograms (53,100 metric tonnes) per 14 lunar days based on the annual sediment budget (using 1,000 kg (one metric tonne) per 1.9 cu m (2.51 cu yd) for conversion).

There are several reasons why the June 1992 estimate of TSM flux is higher than the Beeman sediment budget estimate. The sediment budget is an annual average while the present estimate is a short-term value. The June time period followed by some months the maximum sediment inflow to the system, and these higher inflows probably were temporarily stored in the system, creating conditions that would increase sediment export over average conditions. The typical summer pattern of high midmorning to late afternoon winds has been reported to resuspend winter-deposited sediments on shallows and mudbanks as previously described. Higher than averge winds could contribute to higher than average TSM flux out of the bay.

Winds during the 1992 survey appeared to be typical of the summer season. Figure 23 shows wind components for the period of the survey. There were strong daily variations in wind magnitude with maxima occurring after noon, decreasing to minima after midnight. The strong ebb TSM transport occurred in the early morning hours of June 16 and 17, as seen in Figure 19 (Sheet 2). Winds during these and most other early morning periods were relatively low, as shown in Figure 23. Therefore, the observed maximum ebb transport rates were not correlated with times of high winds. On the contrary, high flood and ebb TSM transport rates occurred during

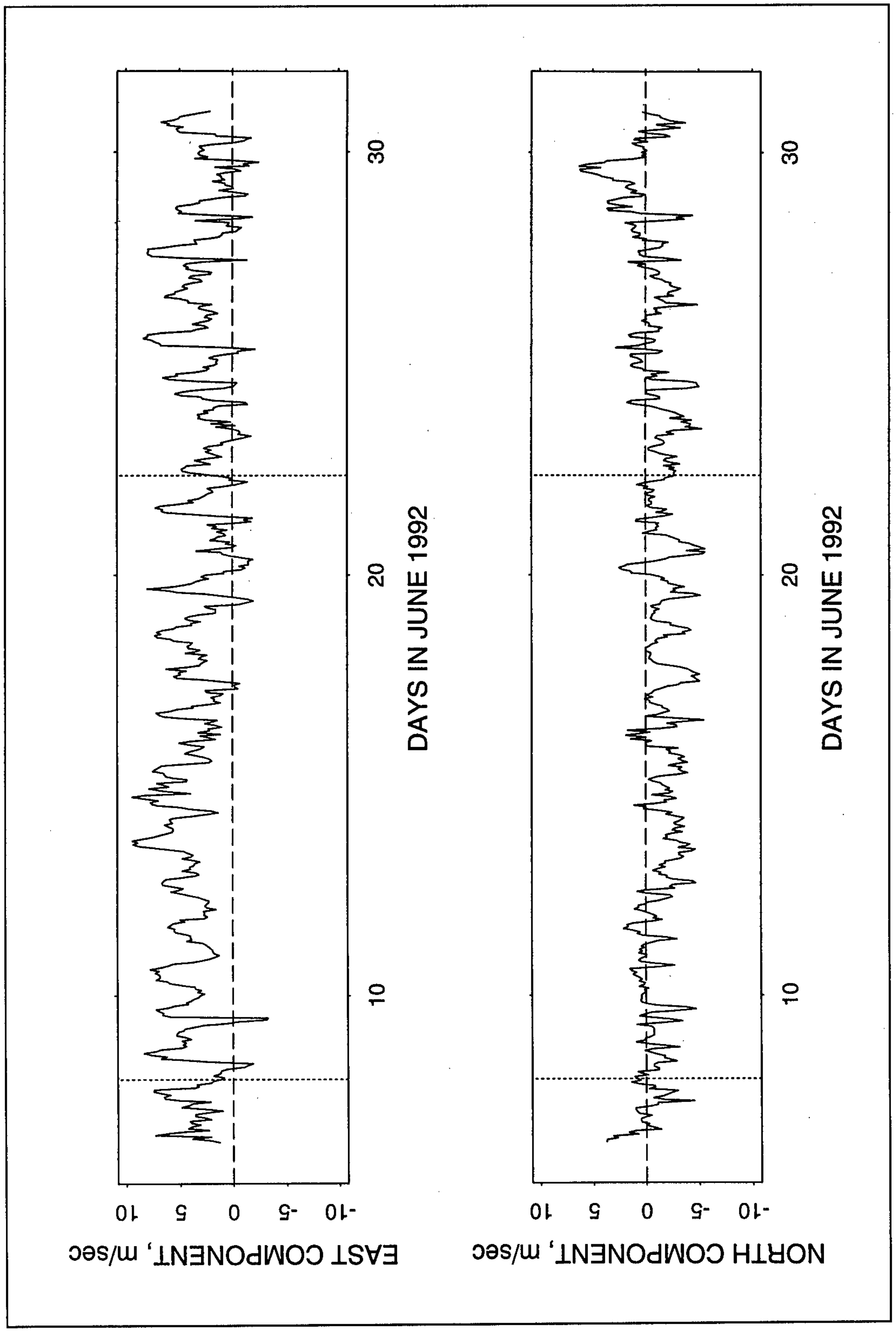


Figure 23. June 1992 wind components for the 1992 field survey (bracketed by dotted lines)

low-wind conditions and therefore appeared to be linked exclusively to tidal conditions.

The observed strong ebb-tidal-phase TSM transport may be linked to tidal drawdown of shallow-water areas. Shallow off-channel areas have lower currents and accumulate fine sediments under most conditions. The bay volume decreases by more than 30 percent between high and low waters during a spring tide (Cheng, Casulli, and Gartner 1993). Water in the shallow off-channel areas empties into channels near lower low water while shallow-water bottoms are exposed to higher current shear stresses, creating resuspension and higher TSM levels. A much greater portion of resuspended material leaves shallow-water areas during ebb phase than on flood phase. The highest average TSM concentrations were observed in channel areas during the latter part of these ebb tides or during the beginning of the subsequent flood tide. TSM data from Ranges 2, 3, and 5 are shown in Figure 24 for 16-18 June 1992, the period during which spring tidal phases were monitored. During the ebb tides starting early on 16 and 17 June, TSM increased markedly at all ranges, although Range 5 was inconclusive on 16 June and Range 3 was missing on 17 June. During 18 June, the flood tide showed the reverse trend at all three ranges.

If tidal drawdown is the mechanism that mobilizes sediments during strong ebb flows, the limitations of tidal excursion make the shallow fringe areas of Central Bay the most likely source for the sediments transported seaward. To balance sediment supplies with losses, the shallow fringe areas must receive and store fine-grained sediment during periods of high river inflow and low tidal currents, which is consistent with previous observations in other parts of the bay system. Ranges 3 and 5 showed greater tidal TSM variability than Range 2, possibly due to greater shallow areas in South and San Pablo Bays relative to Central Bay or greater longitudinal TSM gradients in those areas. Had spring lower low waters occurred during afternoon hours when winds were maximum, it is hypothesized that ebb transport rates might have been even greater.

In other estuarine and riverine systems, a hysteresis between discharge and sediment flux is often observed such that the fluxes at the same increasing and decreasing discharge are not equal. Such hysteresis produces transport asymmetries that can lead to net or residual fluxes of sediment upstream or downstream depending on the location. Settling of particulates is generally responsible for part of the hysteresis in estuaries. Some hysteresis appears to have occurred at Range 2 during both higher ebb and higher flood flows, as shown in Figure 18. The linear relationships developed here did not capture the hysteresis effect. However, Range 2 hysteresis appears to be a secondary effect compared to the strong ebb-flood asymmetry that was identified in the present analysis.

As previously mentioned, the estimated tidal TSM flux from the 1988 data at Range 2 was estimated to be landward. Some additional analyses were performed to resolve the difference between the 1992 and 1988 survey results.

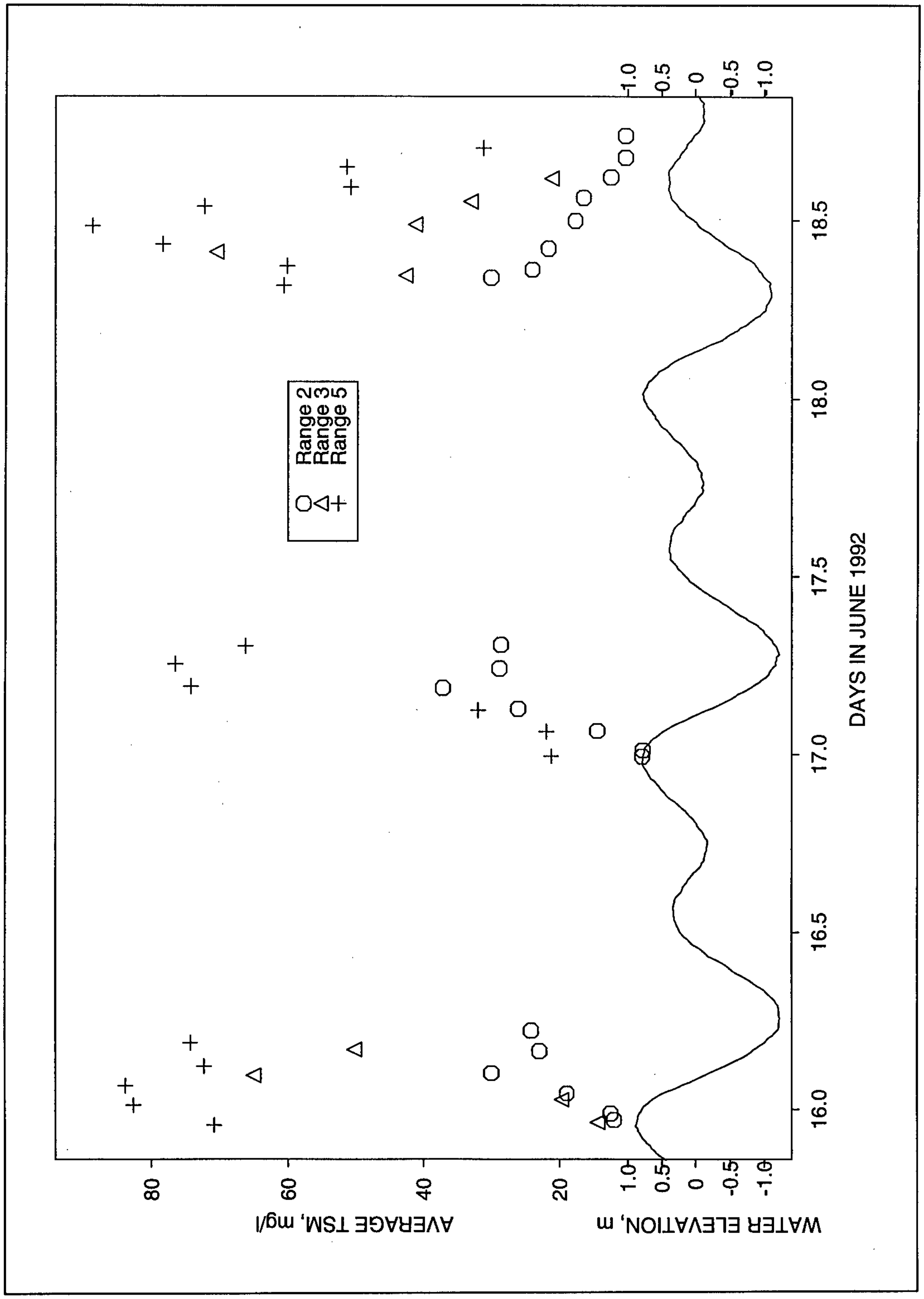


Figure 24. Transect-averaged TSM concentration for Ranges 2, 3, and 5 for the spring tide period

The empirical relationships between water-surface slopes, time derivatives, and tidal flow, and between tidal flow and TSM flux developed from the 1992 data were used to reanalyze the 1988 field data. Discharge and tidal flux time series were created from the 1988 elevation records from TGO1 and TGO3, as was done with the 1992 field data. The discharge and TSM flux were used to create a time-series of TSM concentrations, plotted in Figure 25. The station-averaged (surface, middepth, and bottom) TSM data from each of the three stations across Range 2 were calculated, fit with a smooth line, and plotted in Figure 25.

The 1988 TSM data show some of the same features identified in the analysis of the 1992 data. There was a general drop in TSM concentration level during the lower-high to higher-low water ebb and at the beginning of the strong ebb. The TSM concentration level increased during the latter part of the strong ebb. However, the concentrations during flood tidal phases that followed the higher-high water to lower-low water ebb tides were higher than predicted. During the 1988 survey, only 9 points in the cross section were sampled versus the 25 points sampled during the 1992 survey, which may account for the greater variability in the 1988 data. The sudden wind shift and high-wind conditions that occurred during the 1988 survey, as shown in Figure 26, may have affected TSM concentration levels. The tidal prism method is inaccurate when TSM increases with increased flow, as was documented in the 1992 data. The conclusion of this analysis was that the 1988 data were consistent in some aspects with the 1992 data set, but had greater variability due to sampling limitations and conditions. The 1992 results are deemed to be of a higher quality and more representative of long-term conditions. Only an extensive monitoring program could determine the variability in tidal or spring-neap net sediment fluxes.

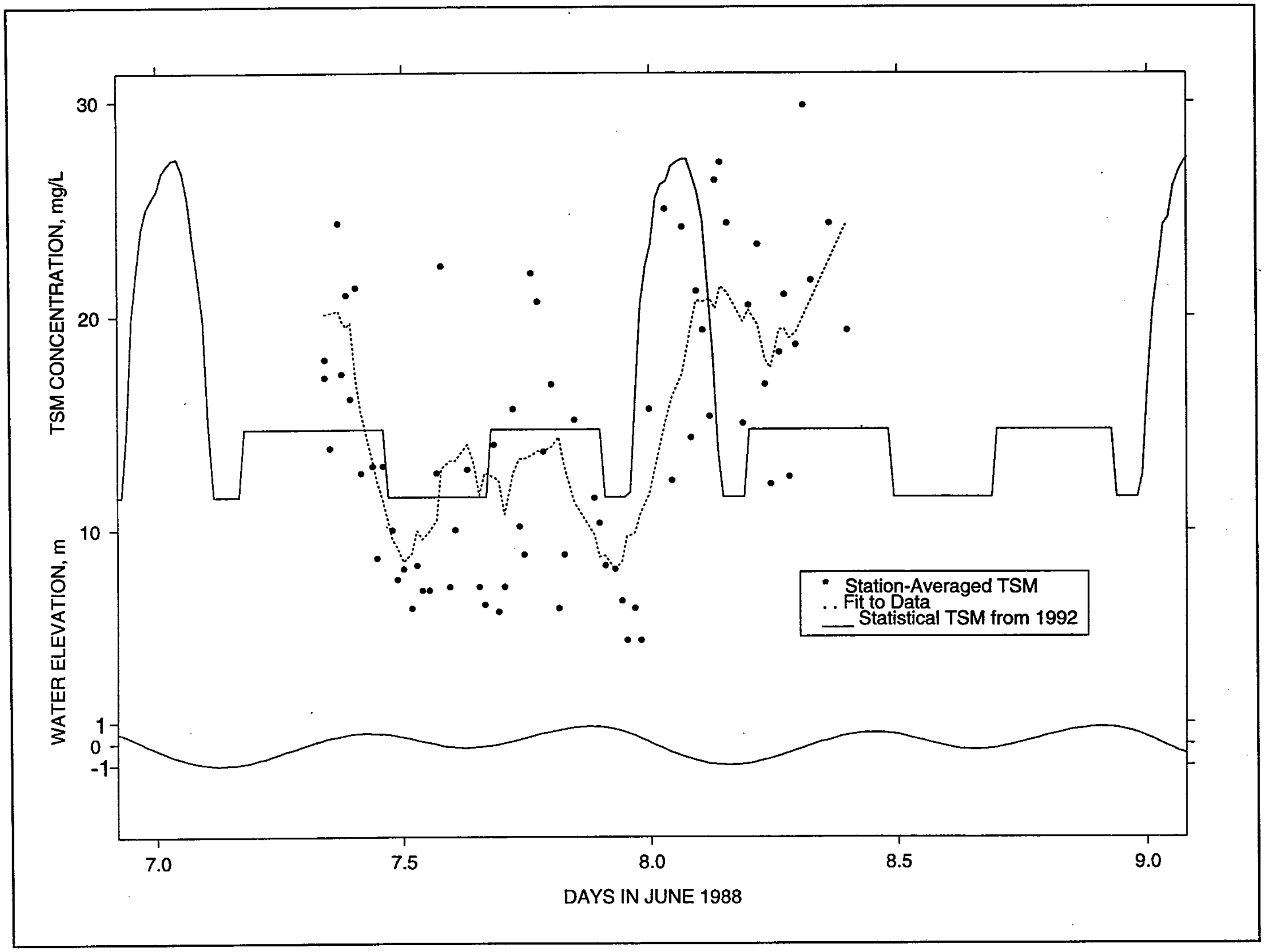


Figure 25. Observed (●) and synthesized (solid line) TSM records for the 1988 field survey (dotted line is trend line for observed TSM)

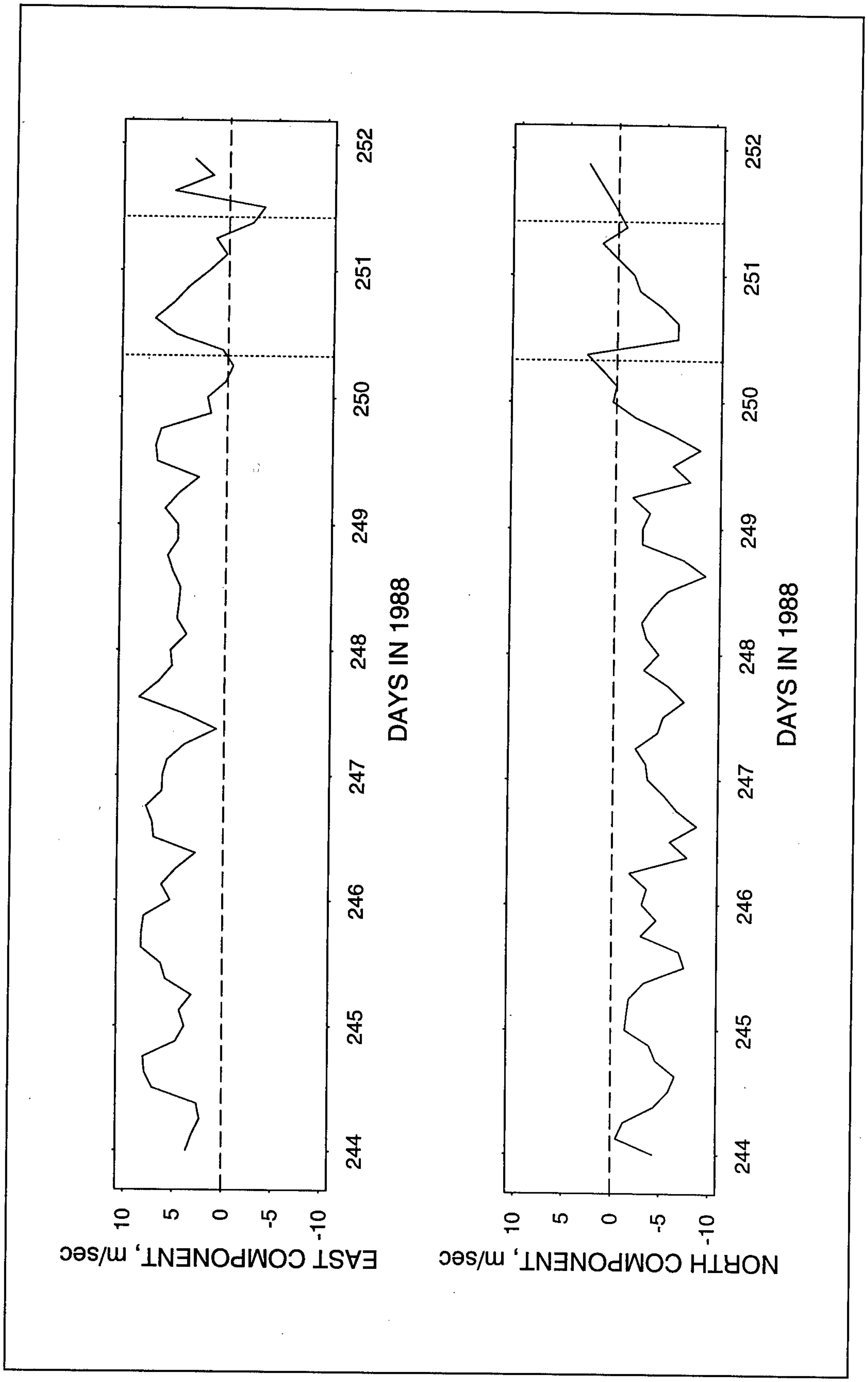


Figure 26. September 1988 wind components for the 1988 field survey (bracketed by dotted lines)

5 Two-Dimensional Sediment Transport Modeling

Simulation Strategy

The sediment transport modeling effort adopted a strategy of simulating only the fine-grained fraction of the system sediments for several reasons. First, the fine-grained, cohesive fraction of the material is the most critical for issues of turbidity plume migration associated with dredged material placement. Concerns about adsorbed contaminants focus on cohesive material. Furthermore, the majority of the ambient system sediments that contribute to resuspension and impact on the background suspended sediment concentrations are cohesive. Finally, the percentage of cohesive material present in most of the sediments in the system results in effective entrapment of sands and coarser silts to the degree that the cohesive bond strengths of the sediment mass largely control sediment mobility, as found by Teeter (1987) for San Francisco Bay dredged material.

The sediment model used for these tests was STUDH, a component of the TABS-MD System. It calculates the advection, dispersion, deposition, and erosion of cohesive and noncohesive sediments in two dimensions (depth-integrated). A more complete description of the model is given in Appendix A of Report 1 of this series.

Two-dimensional hydrodynamic model results, described in Report 1 of this report series, were used to drive the sediment model. Results from the wave model were also used by the sediment model. The sediment model was adjusted by iteratively varying sediment parameters, observing the model response, and adjusting model parameters to closely match observed conditions. Initial suspended sediment concentrations and sediment conditions were varied over expected ranges during the model adjustment process. At the end of the adjustment process, the sediment model was verified to TSM data sets.

Boundary Conditions

Concentration boundary conditions were specified for the sediment transport model at all open water boundaries. The Pacific Ocean boundary condition was a concentration of 15 ppm, which was invoked only at a point on the boundary when the current velocity direction was into the model domain. When flow was leaving the model, the ambient concentration was allowed to flow out of the model. The concentration specified for the upstream delta inflow boundaries was 125 ppm.

The boundaries were located far enough from primary areas so that inconsistencies in flow conditions and concentration levels either resulted in a local adjustment in concentration by local deposition or were minimized by cyclic erosion and deposition. Thus, these inconsistencies will not have a significant influence on the primary areas of investigation. This was evidenced at the ocean boundary by local deposition along the line of elements adjacent to the boundary. At the upper end of the model, local deposition occurred as well, indicating an excessive supply was provided for the low discharge conditions being tested.

Development of Initial Conditions

The procedures used for the simulation of sediment transport were designed to allow for predictive estimates of the sediment transport unbiased by the initial conditions used for the model. Model initialization is an important step in this procedure.

The model was initialized with a uniform layering of cohesive sediments over the entire computational mesh. Ten cohesive layers of varying thickness were specified with progressively greater shear strengths and dry densities with depth in the bed. These properties are presented in Table 2. The sediment model was put through a series of bed initialization runs, which eroded softer layers in response to the local bed shear stress imposed by the combined current and wave energy. After the bed structure reached a relative equilibrium, based on the lack of further net erosion with repeating shear events, a week-long simulation was performed to allow the concentration field to adjust from the initial uniform concentration field. After the initialization simulations for the bed layering structure and the concentration field, the actual simulations were performed for a week for the 1988 and 1992 verification periods using the end result of the initializing simulation as initial conditions for the verification periods.

Table 2
Sediment Model Initial Bed Layering

Layer Number	Thickness, mm	Shear Strength N/m^2	Erosion Rate Constant $g/m^2/sec$	Dry Density kg/m^3
1	5	0.07	0.200	334
2	5	0.10	0.200	450
3	10	0.15	0.200	650
4	25	0.30	0.100	650
5	25	0.50	0.100	650
6	25	0.70	0.100	650
7	30	1.00	0.070	650
8	30	1.50	0.070	650
9	50	3.00	0.070	650
10	100	6.00	0.070	650

Model Coefficients

The sediment model coefficients and parameters used in this study are listed in the following tabulation:

Fall velocity, mm/sec	0.04
Bottom friction, Manning's n	0.02
Initial concentration (initialization)	As calculated in initialization
Turbulent diffusion, m^2/sec	15
River inflow concentration, kg/m^3	125
Ocean boundary concentration, kg/m^3	15
Time-step, sec	900
Critical shear stress for deposition, N/m^2	0.06
Critical shear stress for erosion, N/m^2	0.07

Model coefficients were set after numerous sensitivity model runs, that is, by trial and error during the model adjustment process. The reasonableness of coefficient values was checked by their consistency with laboratory and field observations and previous model studies.

The fall velocity used was in the lower range of those observed during laboratory analysis of San Francisco Bay sediments (Teeter 1987). Kranck and Milligan (1992) found water column aggregate settling velocities in San Francisco Bay to be more than an order of magnitude greater than the value used in the model. However, in the 2-D sediment transport model, fall velocity represents the average depositional velocity of fine-grained aggregates. Observations from laboratory tests show that depositional velocities of the constituent particles tend to be much lower than the settling velocities for fine aggregates.

The bottom friction coefficient, used in the sediment model to calculate shear stress, was selected to be in the mean range of the friction used in the hydrodynamic model. The bed shear stress acting to erode fine sediments is that component of shear stress acting directly on sediment grains. Thus, eroding shear stresses are somewhat less than the total hydrodynamic shear stress, the difference being shear stress associated with bed forms and large-scale roughness.

The critical shear stresses for erosion and deposition listed in the tabulation on the preceding page are the properties of material newly deposited from suspension and are independent from the shear stresses of material within the bed layers described earlier.

Verification

The verification of the sediment transport model was based on the reproduction of observed suspended sediment concentrations and more generally on the suspended sediment fluxes at monitored cross sections. The model was verified to the September 1988 and June 1992 WES field data sets.

Sediment concentrations

The comparisons of the computed and measured suspended sediment concentrations are presented in Plates 1-15 for the 1992 verification. The station locations are presented in Figure 5.

Sediment fluxes

The data collected in 1992 enabled the estimate of sediment fluxes for the monitored cross sections in Central Bay. Estimated sediment fluxes from the field data are compared with model sediment fluxes at Ranges 2, 3, and 5 in Plates 16-18. The fluxes at Range 2 compare favorably between model and field observations, but are lower in the model for Ranges 3 and 5. The regressions used in developing these flux estimates were less accurate for Ranges 3 and 5 than for Range 2.

The sediment flux is correlated with the water discharge for each of the verification ranges in 1992 in Plates 19-21. Each plate includes a single overall linear regression fit of the fluxes for model and field data.

Discussion

The 2-D sediment transport model includes process descriptors or algorithms for a uniform fine-grained sediment material acted on by wave and current shear stresses. Only suspended transport is considered as this is the dominant mode of transport associated with fine-grained sediment. Because of the lack of understanding and data on the behavior of fine-grained sediment and use of 2-D calculations, the model lacks some features known to be important at certain sites. However, the model is useful, especially in the sensitivity mode, to examine the effects of disturbances to the system.

The sediment model reproduced cross-sectional mean suspended sediment concentrations more accurately than time-histories at individual stations. Suspended sediment fluctuations or pulses at individual stations were not well reproduced, but transect fluxes were reproduced reasonably well, indicating that average concentrations were reproduced. The temporal and spatial variability in observed TSM fields may be linked to turbulent boundary layer ejection, nonuniform bed erodibility, or tidal drawdown as discussed in Chapter 4. During the initialization process, the sediment bed comes into equilibrium with the flow such that the erodibility of the bed surface is spatially varying. However, the full range of sediment variability is not represented in the model as the effects of fluidization by waves, fluid mud, and fine-grained mixtures are not included. The highly variable properties of fine-grained sediments are not fully described by the present generation of sediment models. The adjusted sediment model does reasonably well at reproducing average conditions and fluxes.

6 Conclusions

Field observations showed an observed net transport of suspended sediment seaward at the Golden Gate (Range 2) over the neap to spring sampling period. The total net transport was 188×10^6 kg (188,000 metric tonnes) seaward over 14 lunar days. The net transport was dominated by suspended sediment fluxes occurring during the stronger ebb flows. Fluxes during the ebb flows averaged 44 percent greater than the flood flows, and instantaneous strong ebb TSM fluxes were often more than twice those on flood tidal phases. The observed net seaward fluxes were in general agreement, though somewhat higher, with the LTMS sediment budget results taken over an equivalent time scale.

The strong ebb-tidal-phase TSM transport was hypothesized to be linked to tidal drawdown of shallow-water areas. The concentration of ebb flow near lower low water increased erosion forces and mobilized sediments from shallow areas. Wind forcing did not appear important to this process. Suspended sediment concentrations increased during the strongest part of the ebb at all Central Bay sampling ranges.

Suspended concentrations in Central Bay quickly return to normal levels after the passage of peak ebb flows. This supports the concept that typical fine-grained suspended sediments undergo cyclic erosion and deposition many times before either finding permanent residence in a lower energy shallow part of Central Bay or exiting the system, most likely in the seaward direction.

Spatial variability in the TSM fields was relatively large, with standard deviations divided by mean values of about 0.5. Some characteristics of the acoustic transects repeated, such as the ebb plume formed by Raccoon Strait on the Golden Gate range. Other factors such as boundary layer ejection, nonuniform sediment bed erodibility, and 3-D effects may have also contributed to TSM variability. The backscatter intensity measurements correlated well with TSM especially on the Golden Gate range where a broadband ADCP unit was employed.

The numerical sediment model reproduced the tidal flux across ranges adequately. Instantaneous TSM concentrations and temporal variability at a point were not predicted as accurately by the model as was sediment transport over a cross section. The model did not fully capture the tidal drawdown

effect. However, the model should be a useful tool in predicting general transport patterns in Central Bay provided the results are interpreted in light of the 2-D approximation and the verification results.

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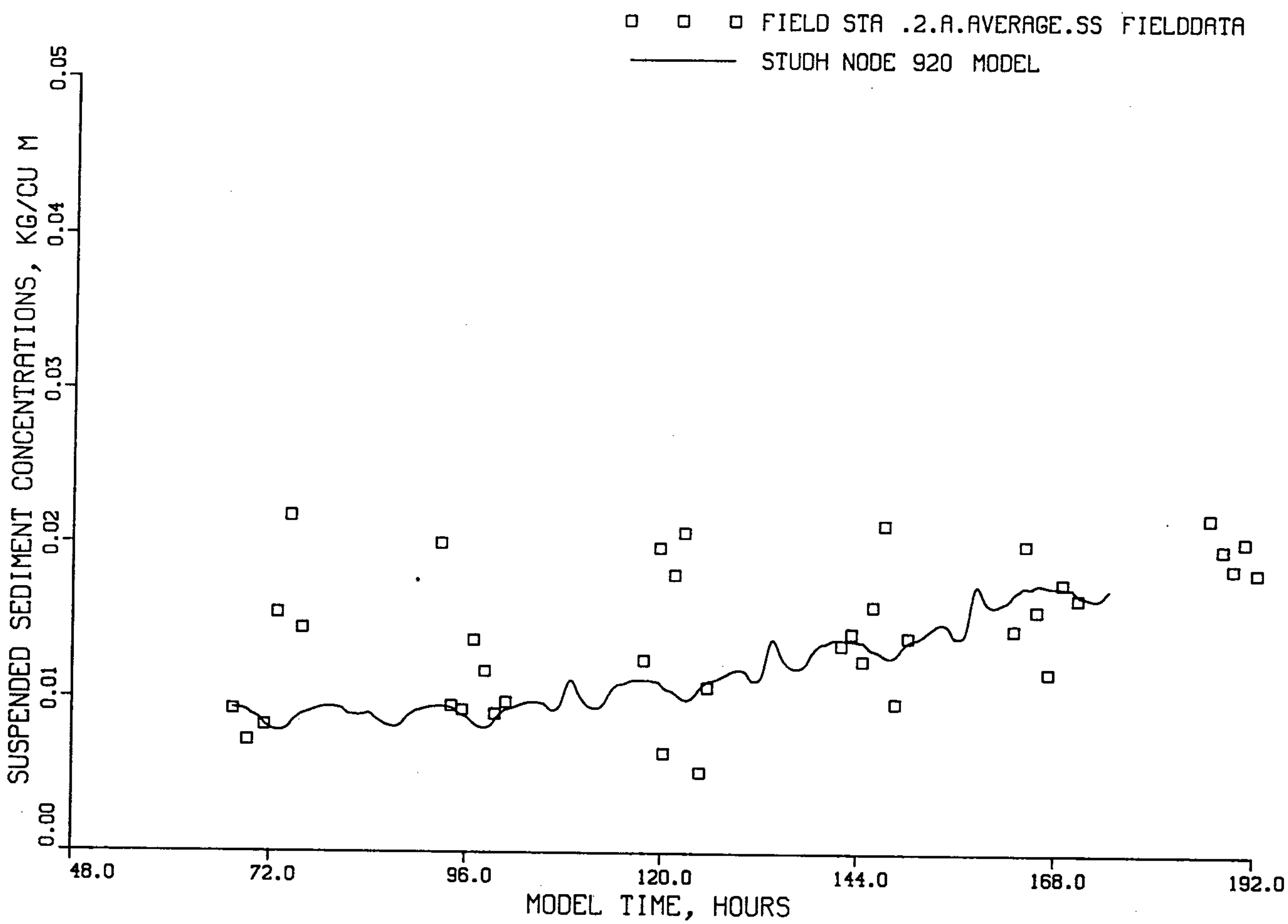


SUSPENDED SEDIMENT CONCENTRATION COMPARISON
BETWEEN FIELD DATA AND MODEL DATA, STATION 2A

Plate 1

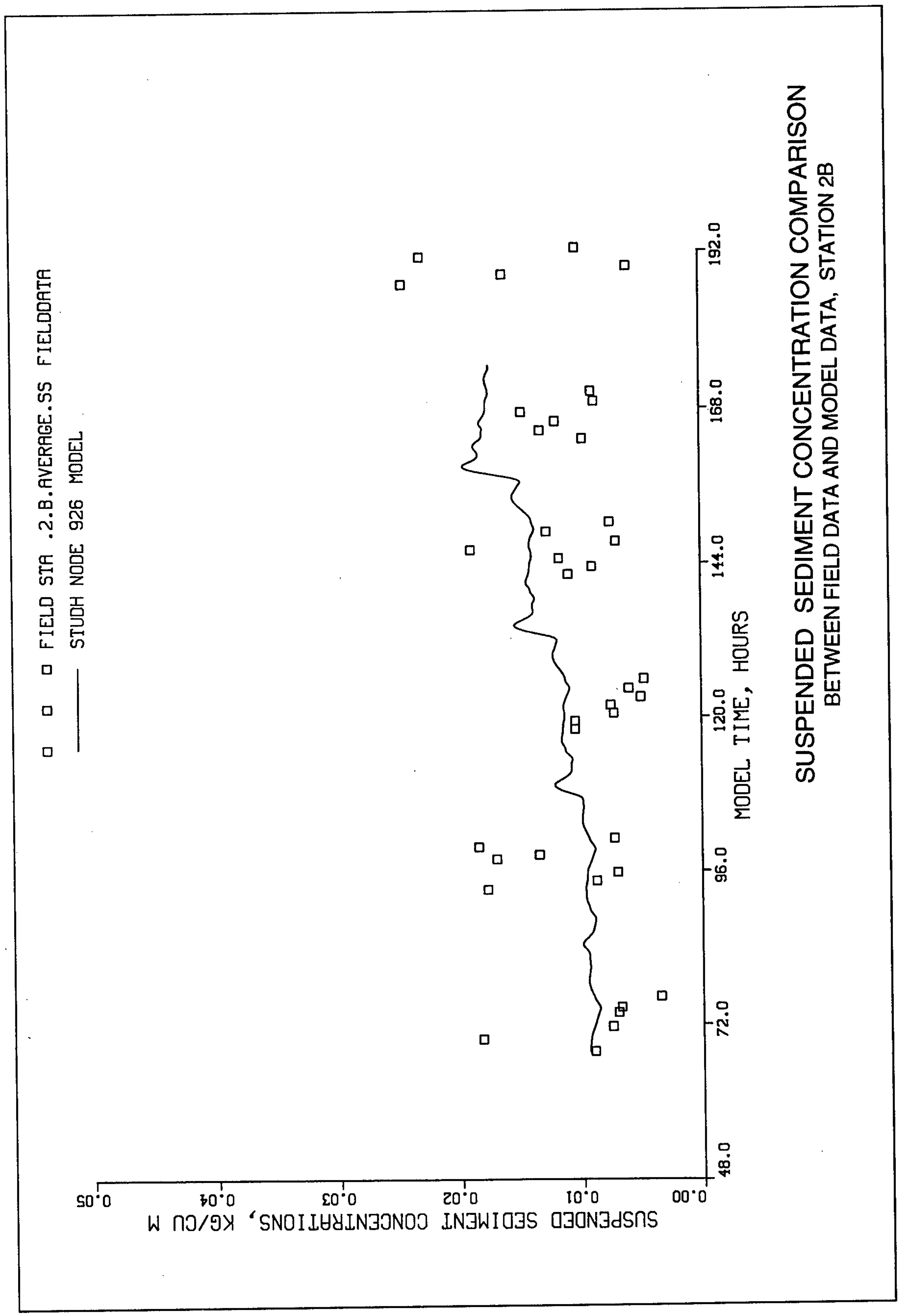
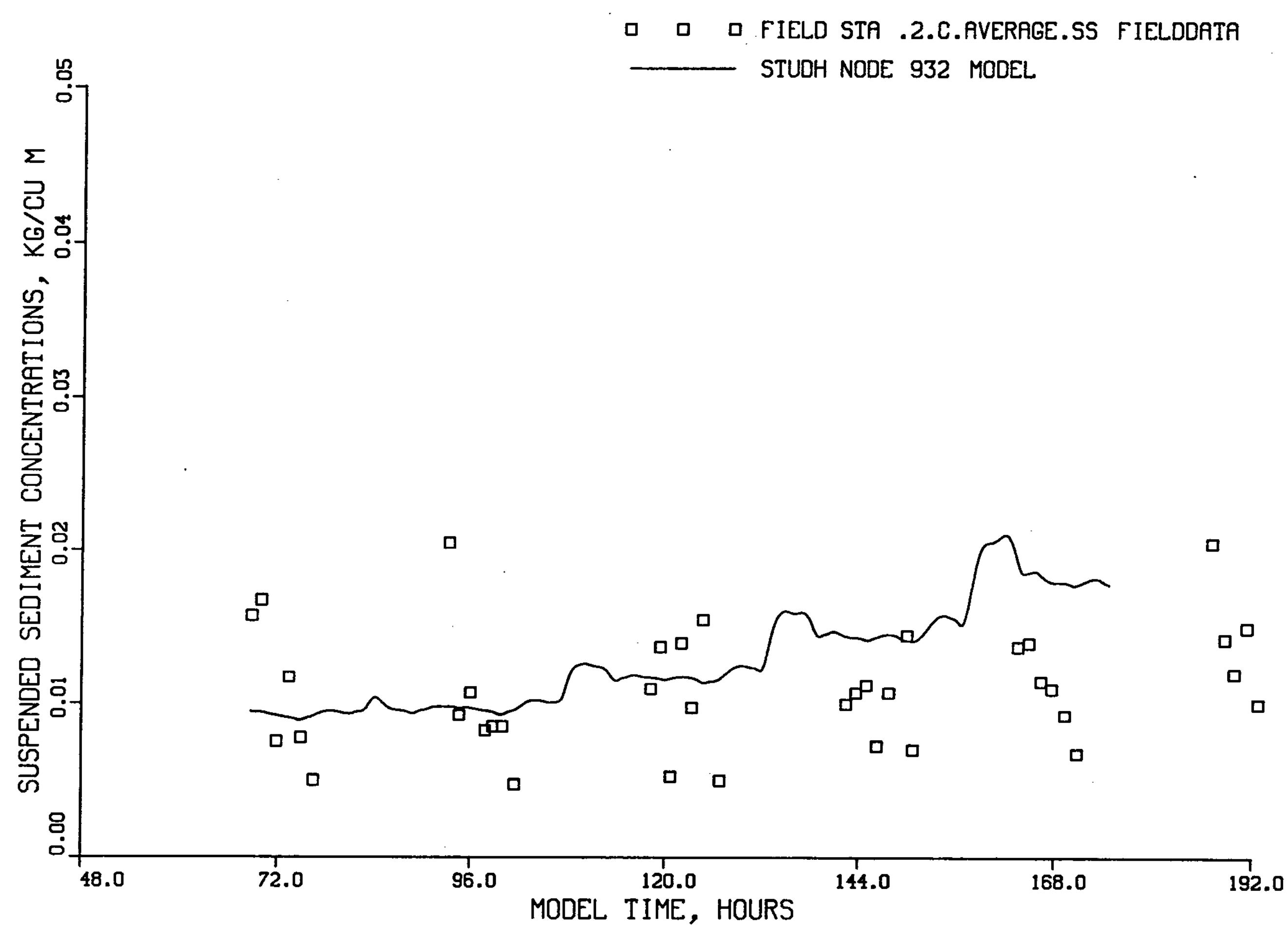
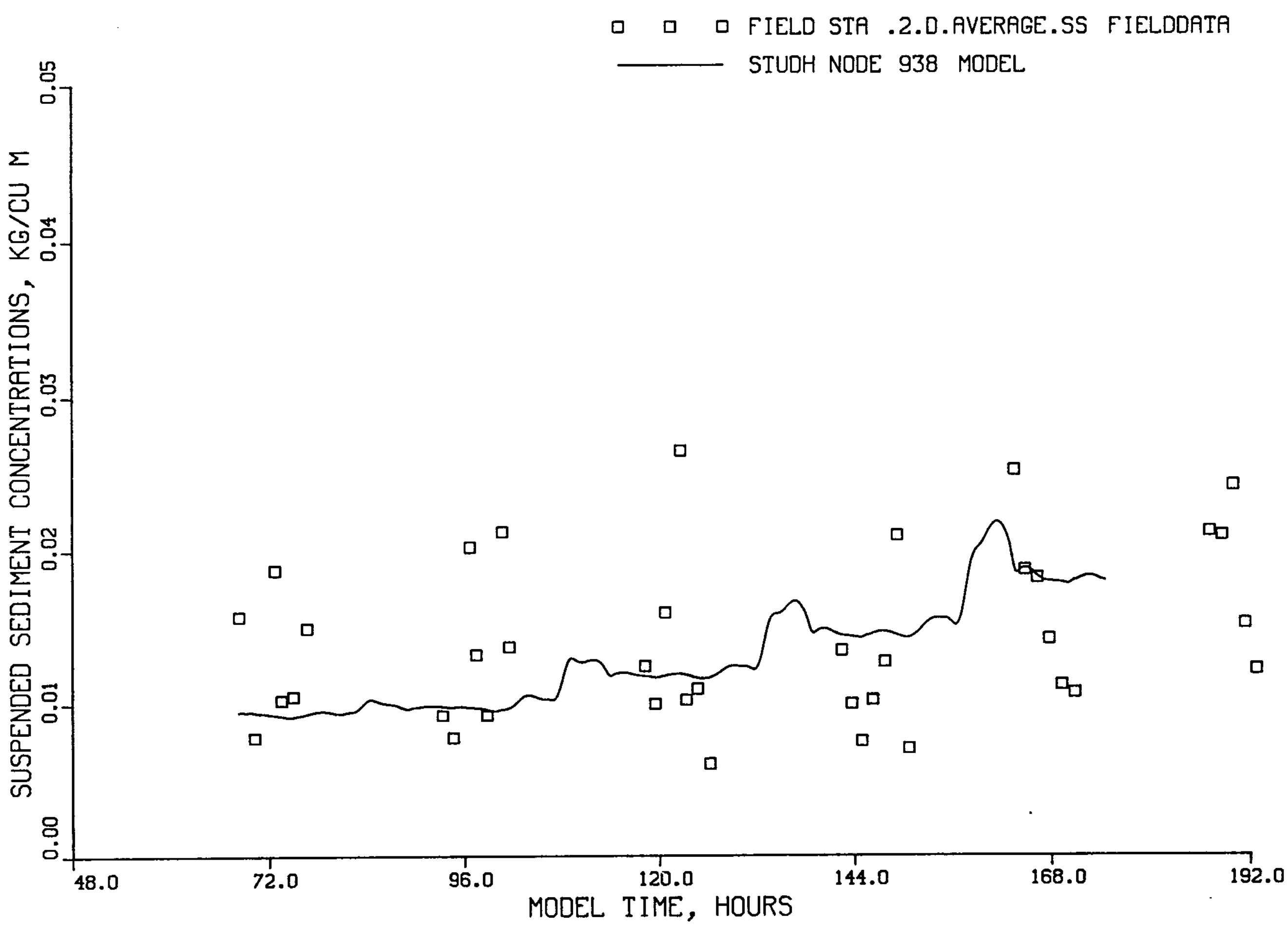

□ □ □ FIELD STA .2.B.AVERAGE.SS FIELDDATA
——— STUDH NODE 926 MODEL
SUSPENDED SEDIMENT CONCENTRATIONS, KG/CU M
0.00
0.01
0.02
0.03
0.04
0.05
48.0
72.0
96.0
120.0
144.0
168.0
192.0
MODEL TIME, HOURS
SUSPENDED SEDIMENT CONCENTRATION COMPARISON
BETWEEN FIELD DATA AND MODEL DATA, STATION 2B

Plate 2

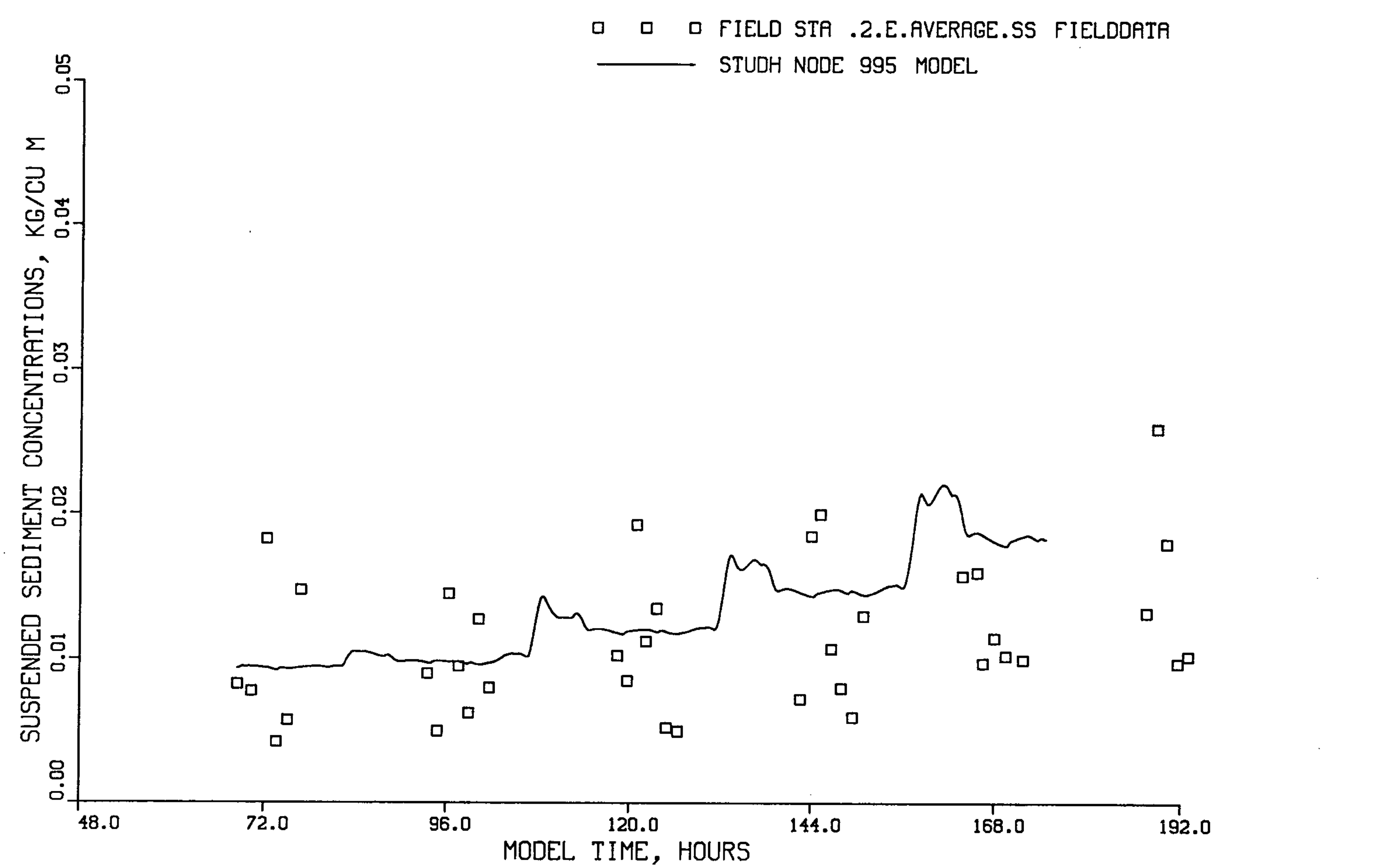


SUSPENDED SEDIMENT CONCENTRATION COMPARISON
BETWEEN FIELD DATA AND MODEL DATA, STATION 2C



SUSPENDED SEDIMENT CONCENTRATION COMPARISON
BETWEEN FIELD DATA AND MODEL DATA, STATION 2D

Plate 4



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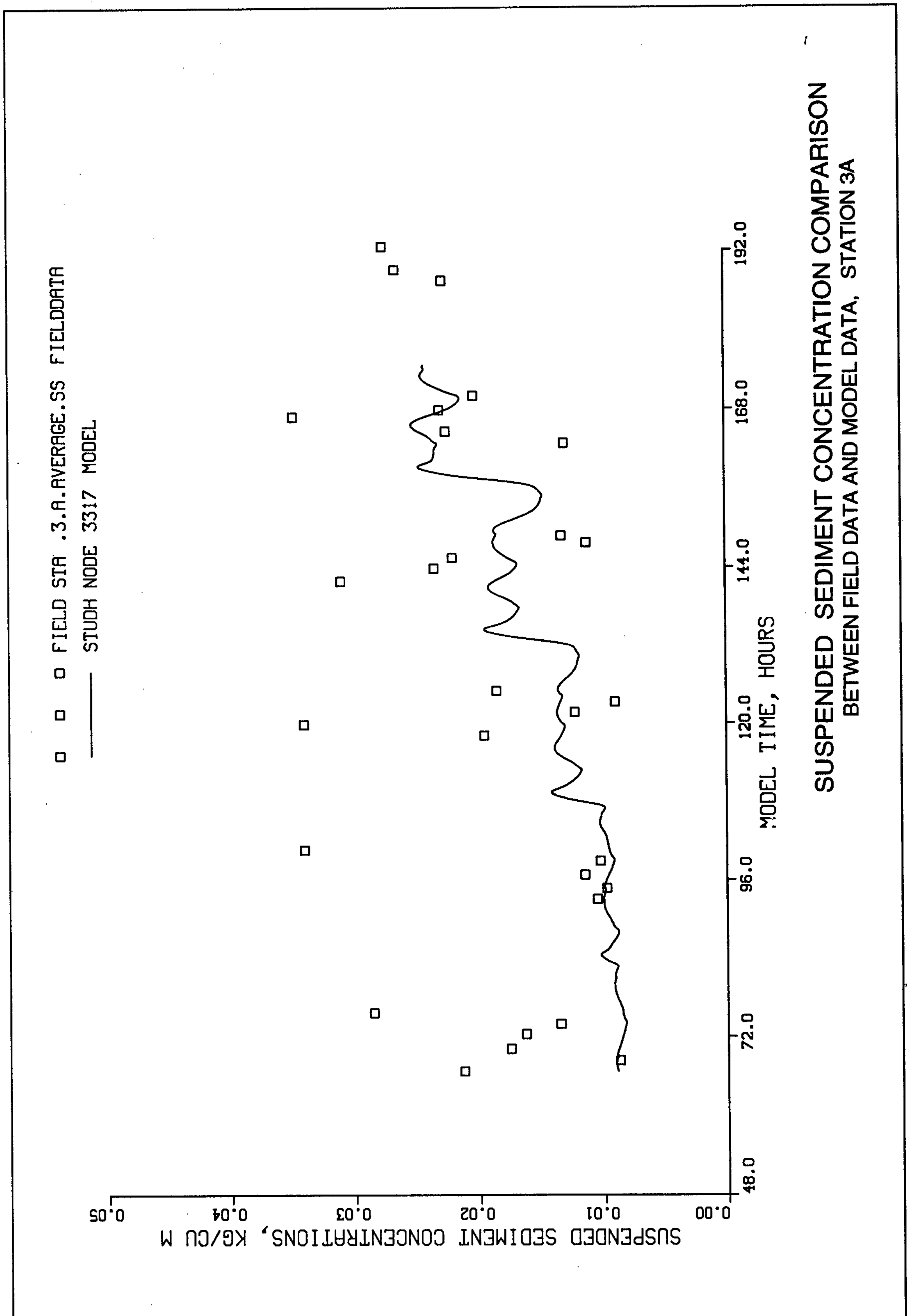
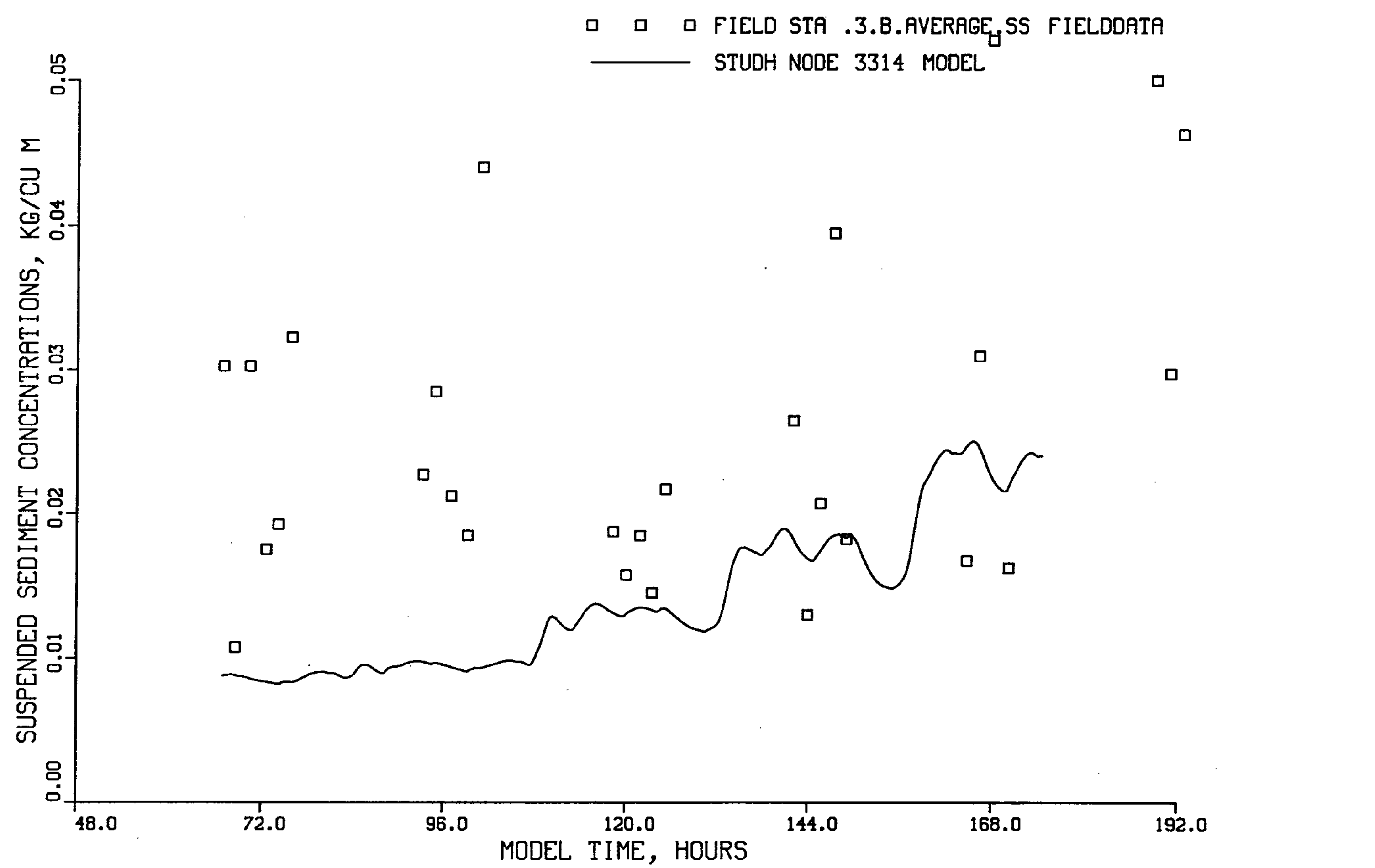

SUSPENDED SEDIMENT CONCENTRATION COMPARISON
BETWEEN FIELD DATA AND MODEL DATA, STATION 3A
FIELD STA .3.A.AVERAGE.SS FIELDDATA
STUDH NODE 3317 MODEL
MODEL TIME, HOURS
48.0
72.0
96.0
120.0
144.0
168.0
192.0
SUSPENDED SEDIMENT CONCENTRATIONS, KG/CU M
0.00
0.01
0.02
0.03
0.04
0.05

Plate 6



SUSPENDED SEDIMENT CONCENTRATION COMPARISON
BETWEEN FIELD DATA AND MODEL DATA, STATION 3B

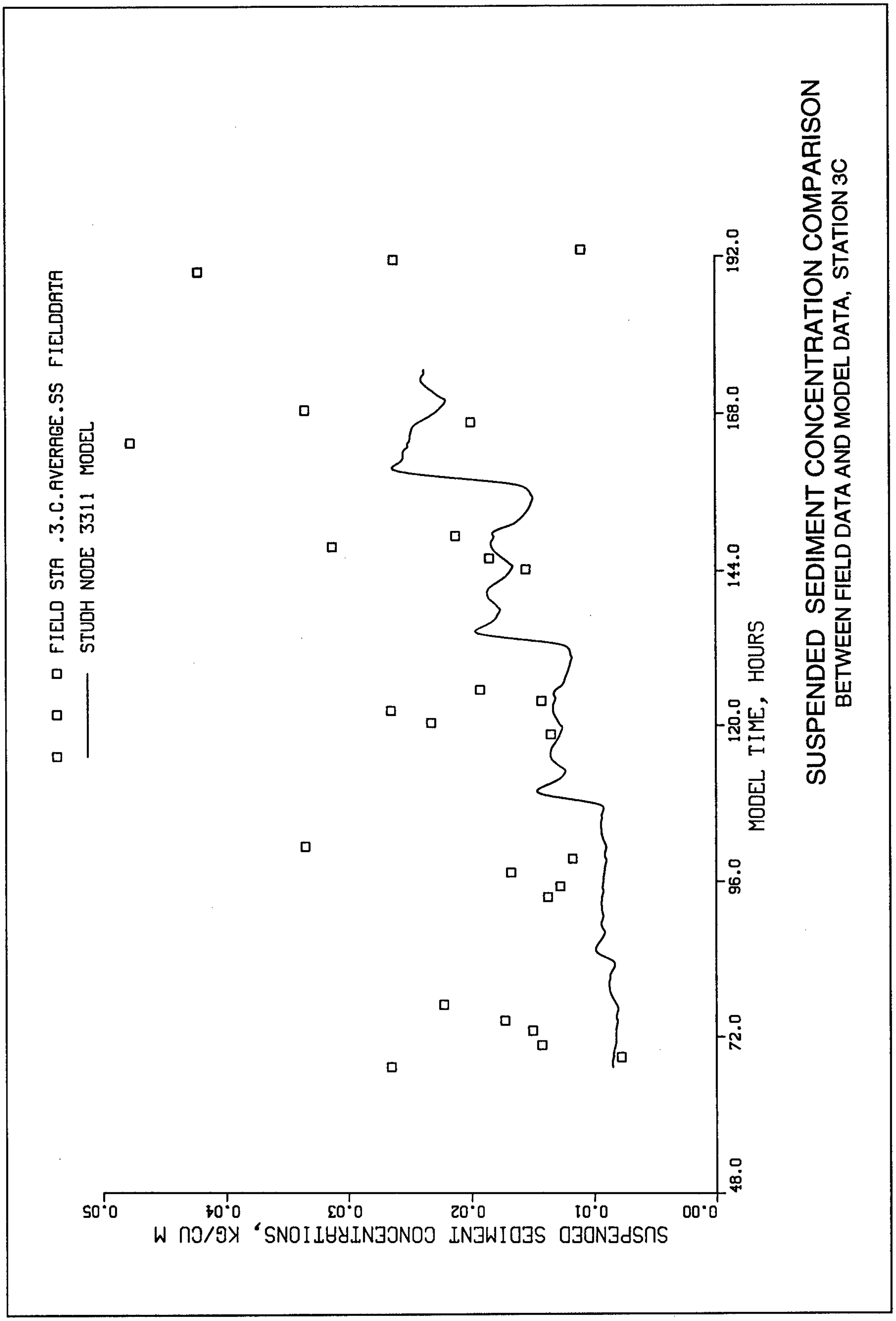
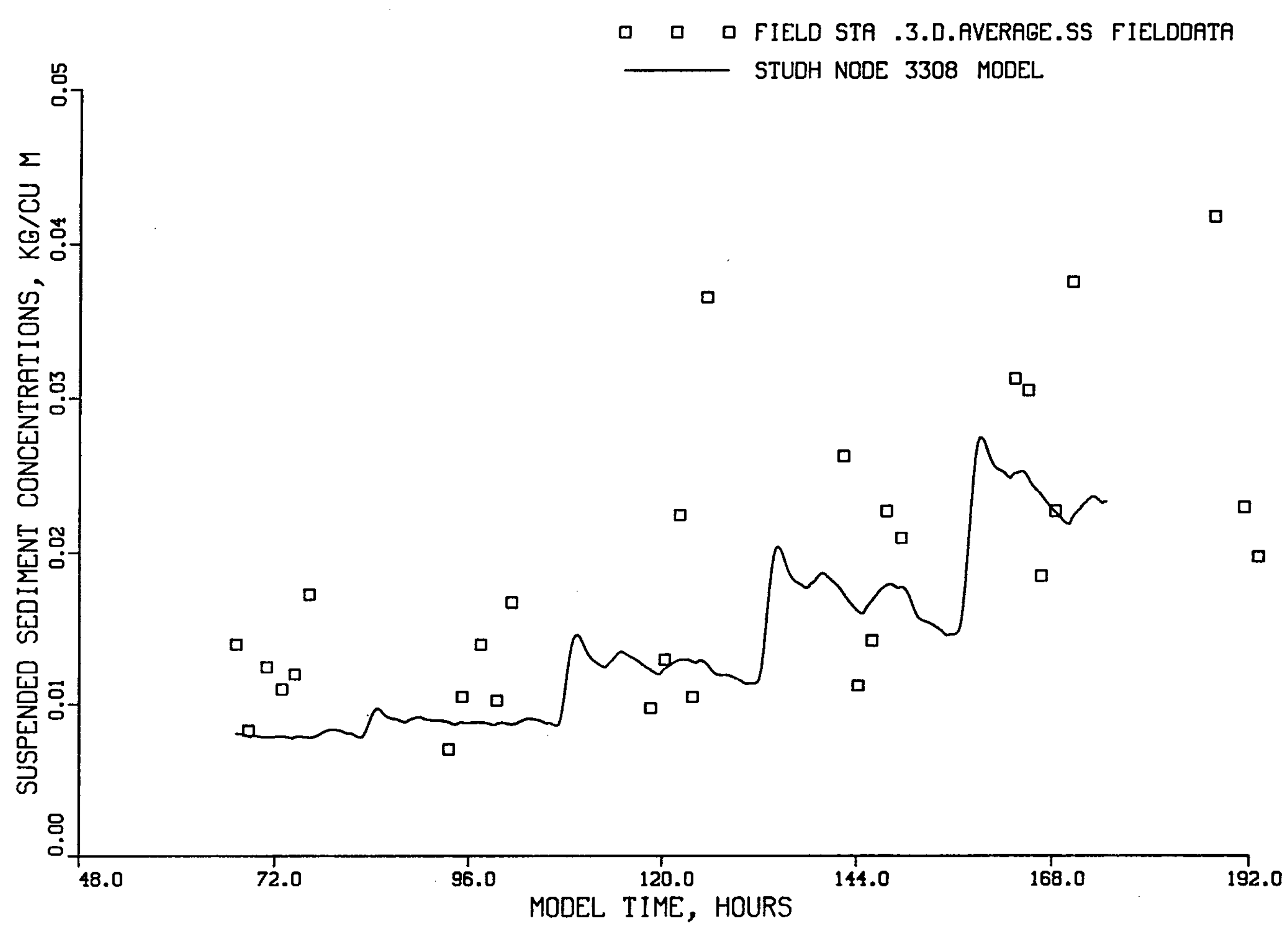
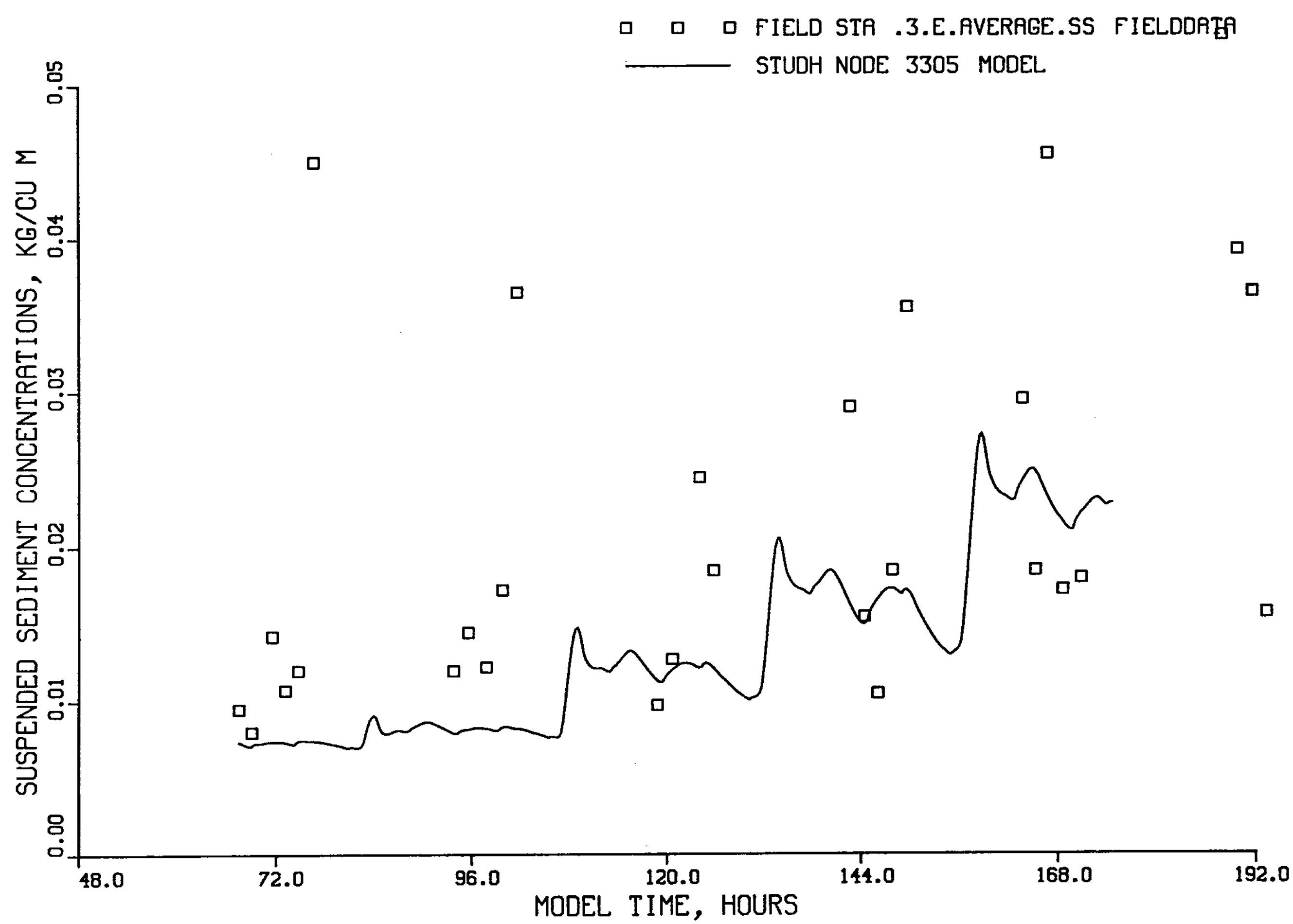

SUSPENDED SEDIMENT CONCENTRATION COMPARISON
BETWEEN FIELD DATA AND MODEL DATA, STATION 3C
FIELD STA .3.C.AVERAGE.SS FIELDDATA
STUDH NODE 3311 MODEL
MODEL TIME, HOURS
48.0
72.0
96.0
120.0
144.0
168.0
192.0
SUSPENDED SEDIMENT CONCENTRATIONS, KG/CU M
0.00
0.01
0.02
0.03
0.04
0.05

Plate 8

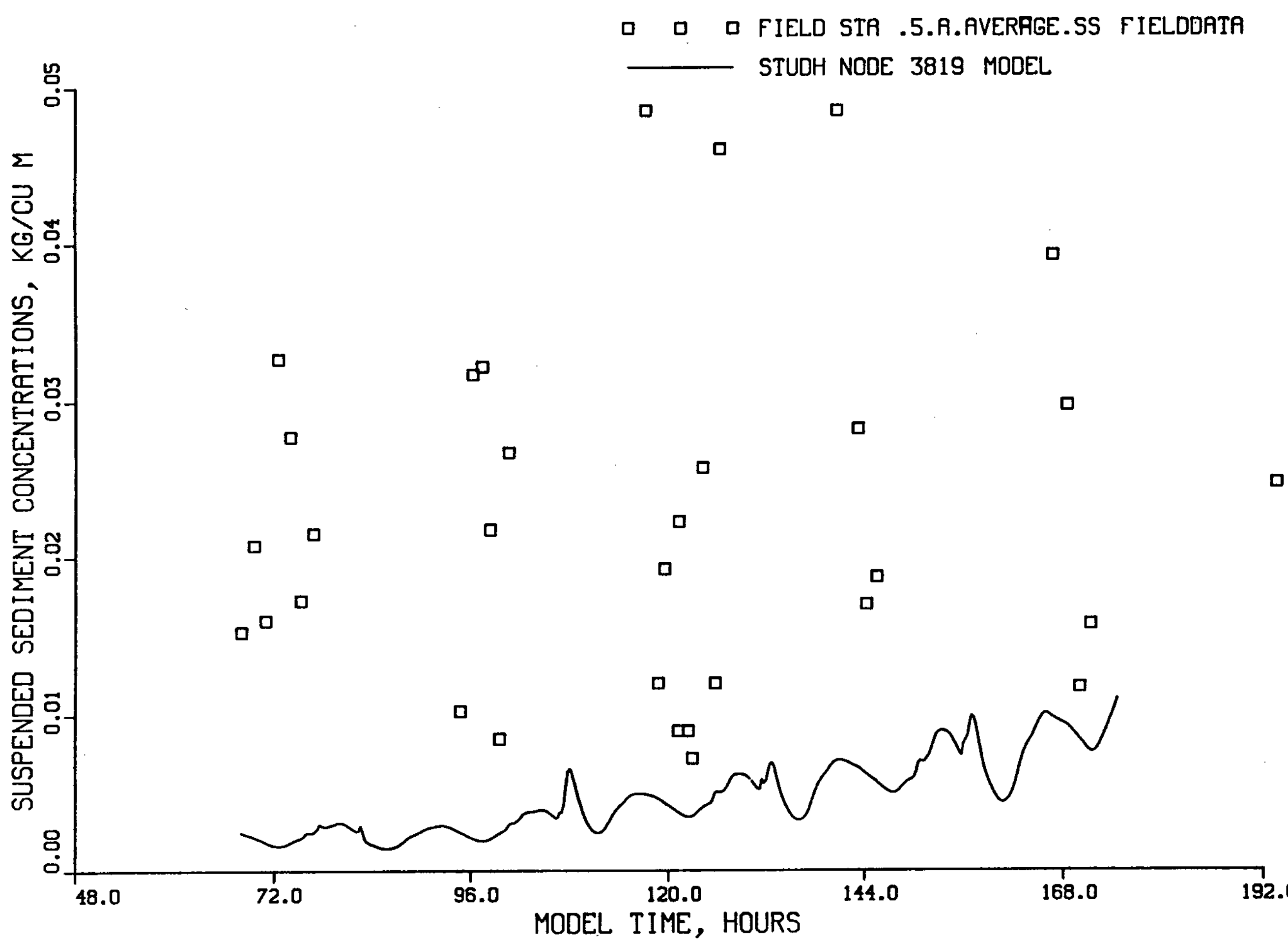


SUSPENDED SEDIMENT CONCENTRATION COMPARISON
BETWEEN FIELD DATA AND MODEL DATA, STATION 3D

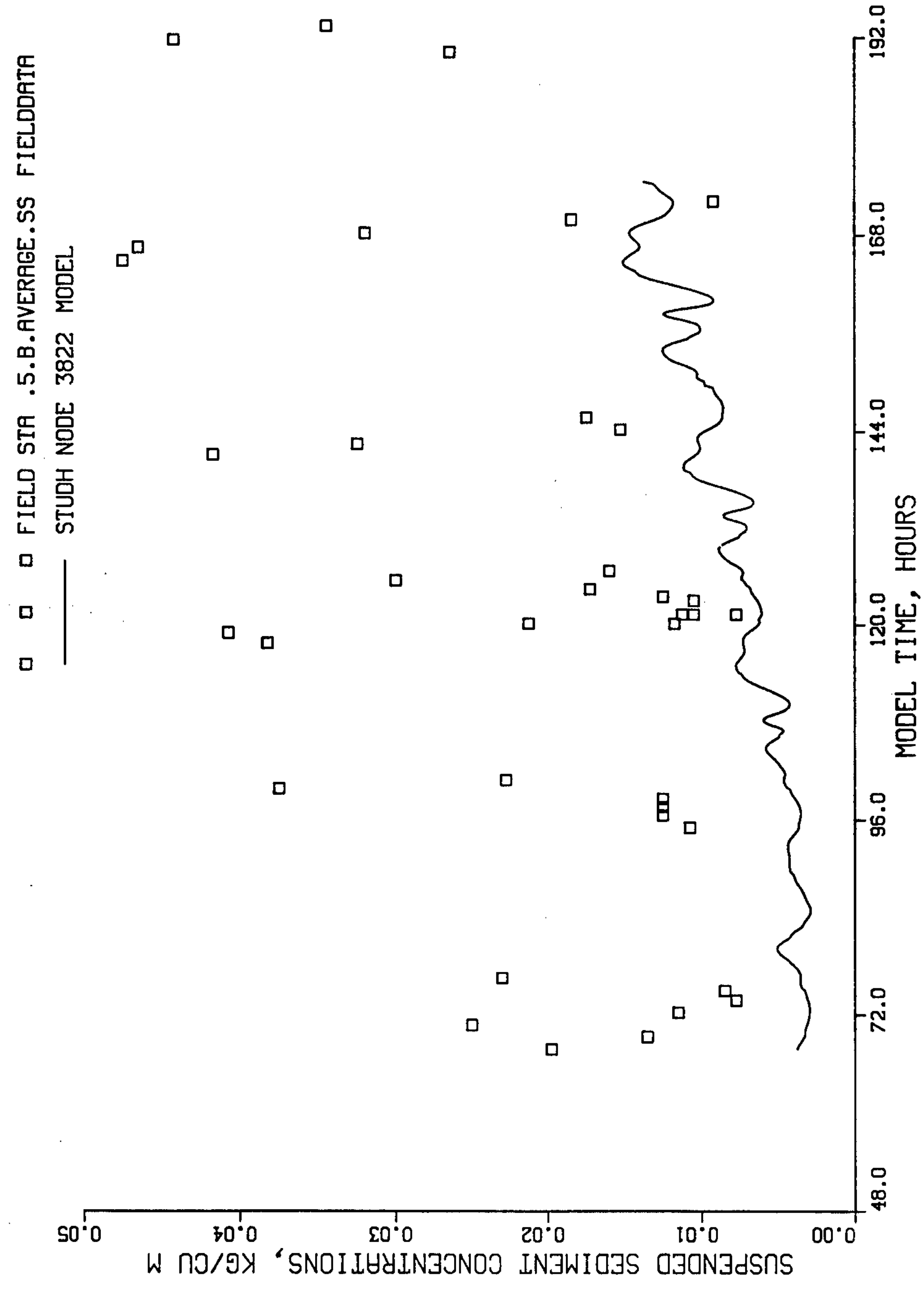


SUSPENDED SEDIMENT CONCENTRATION COMPARISON
BETWEEN FIELD DATA AND MODEL DATA, STATION 3E

Plate 10

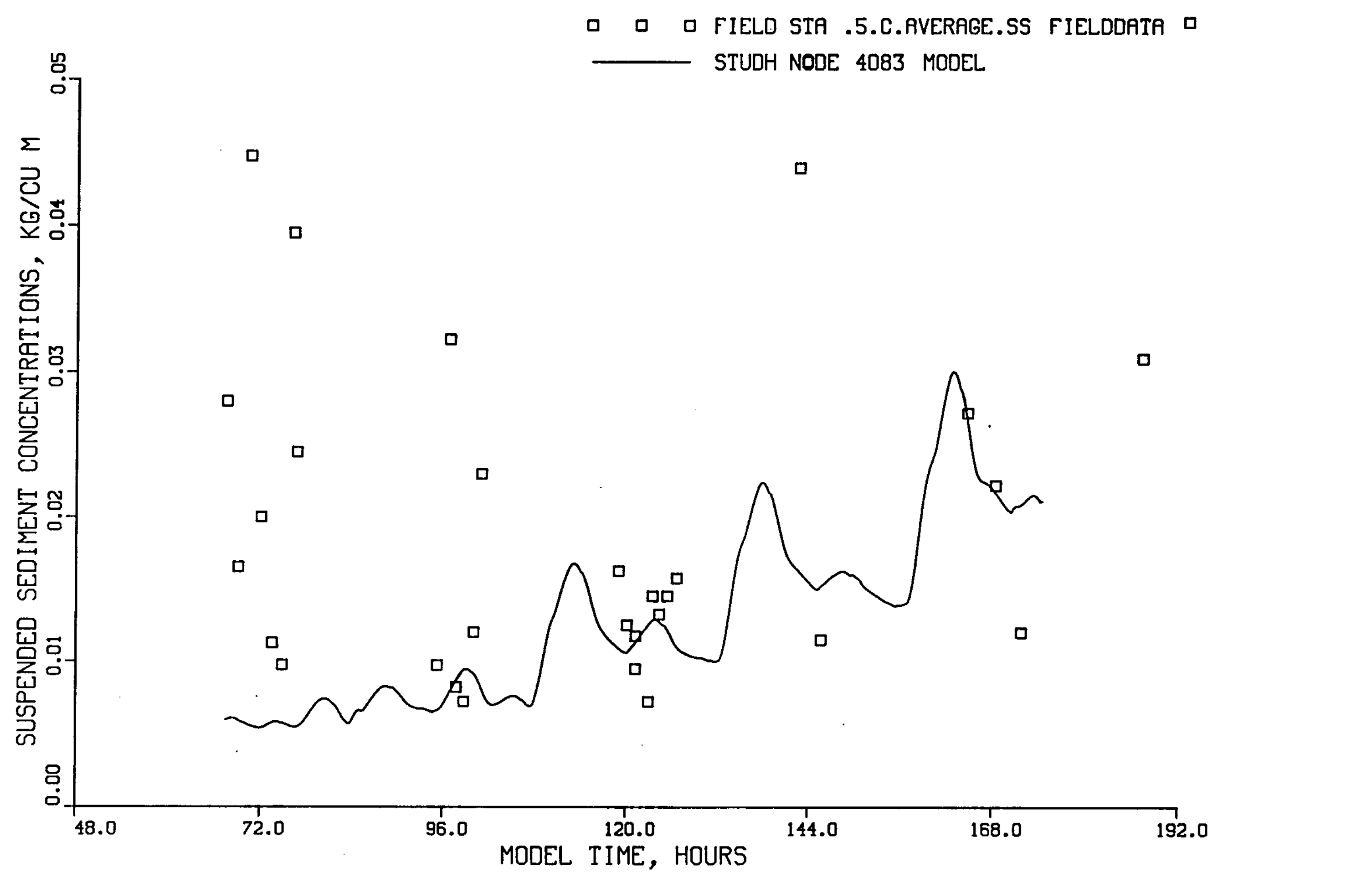


SUSPENDED SEDIMENT CONCENTRATION COMPARISON
BETWEEN FIELD DATA AND MODEL DATA, STATION 5A

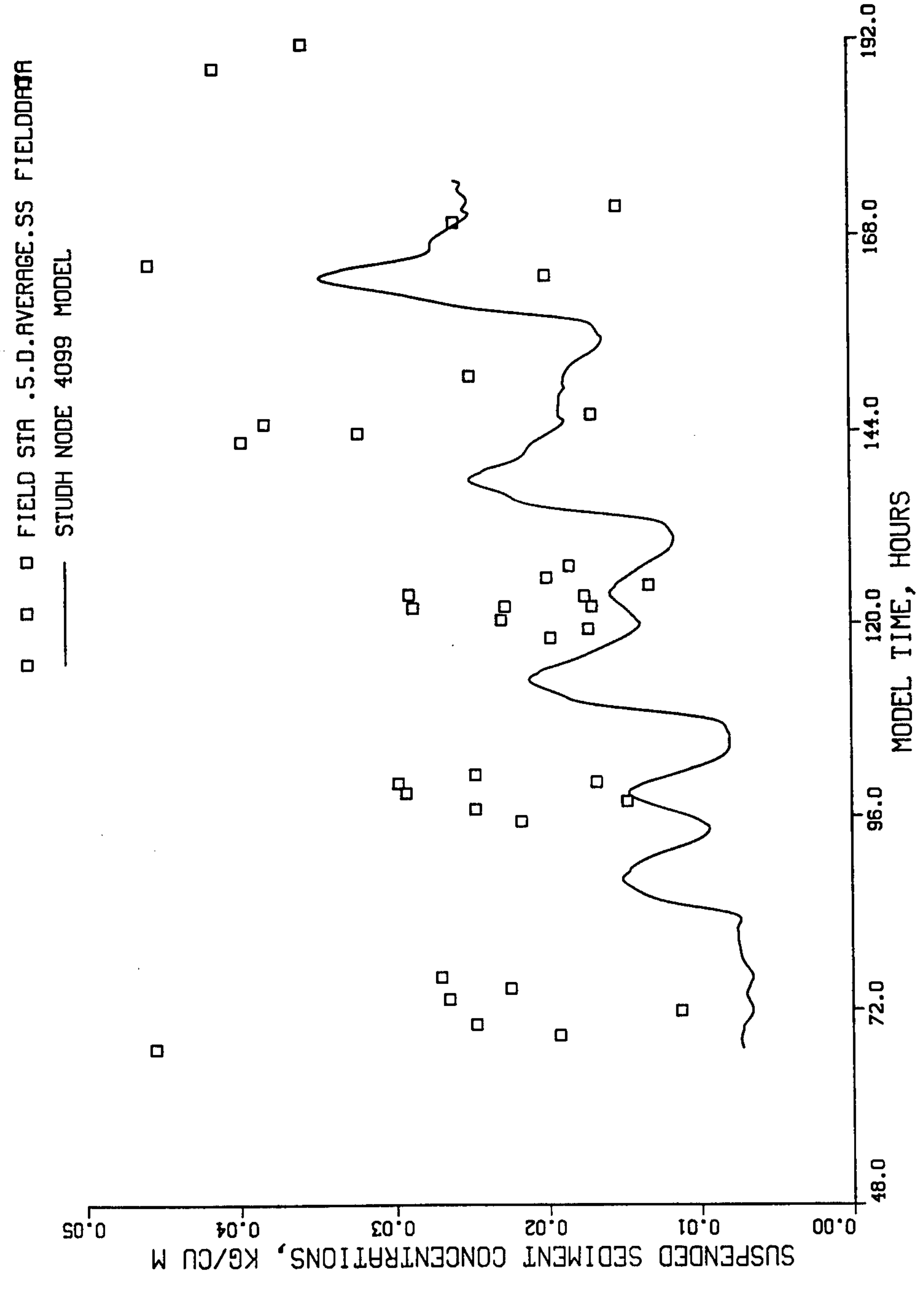


SUSPENDED SEDIMENT CONCENTRATION COMPARISON
BETWEEN FIELD DATA AND MODEL DATA, STATION 5B

Plate 12



SUSPENDED SEDIMENT CONCENTRATION COMPARISON
BETWEEN FIELD DATA AND MODEL DATA, STATION 5C



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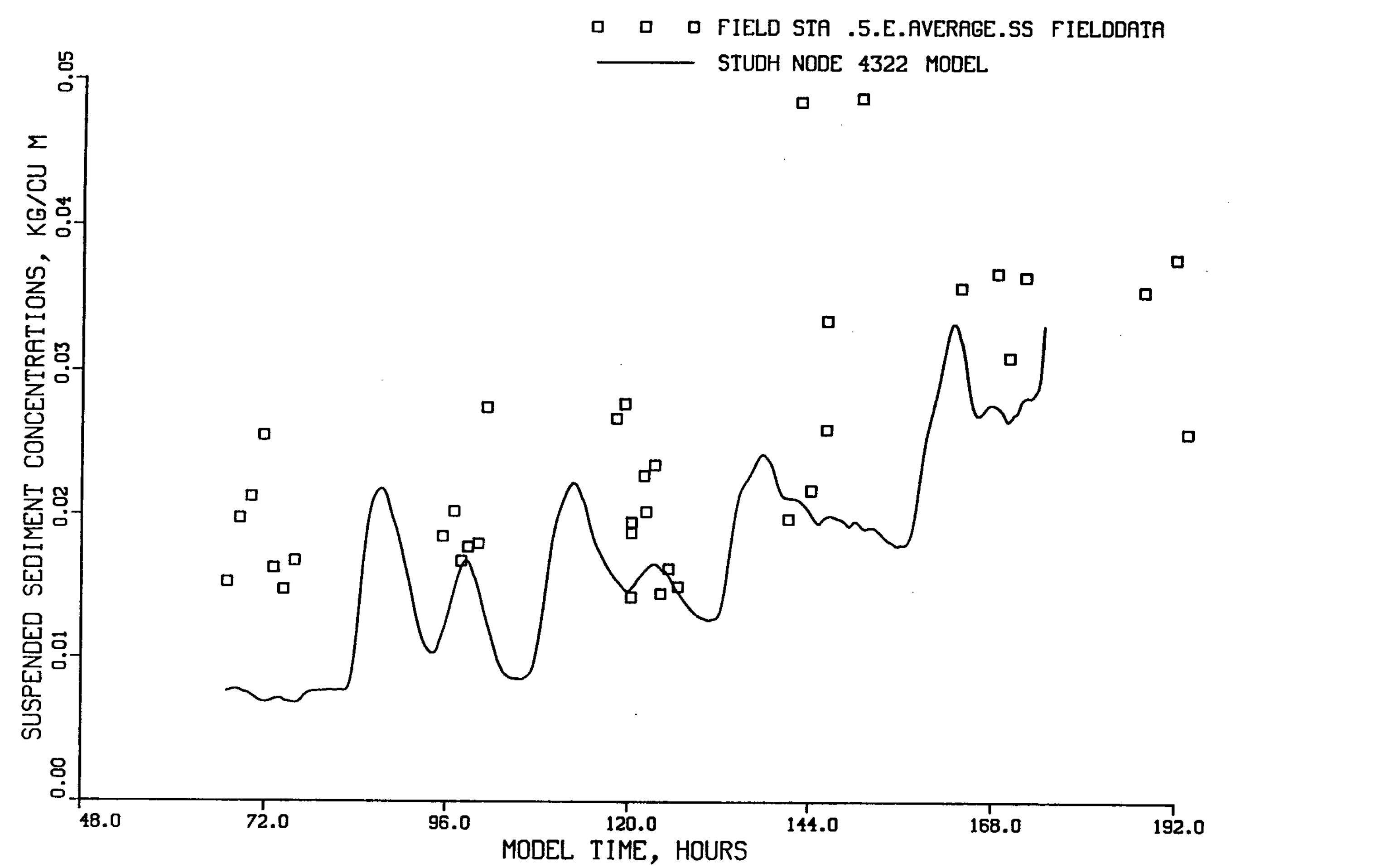

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BETWEEN FIELD DATA AND MODEL DATA, STATION 5E

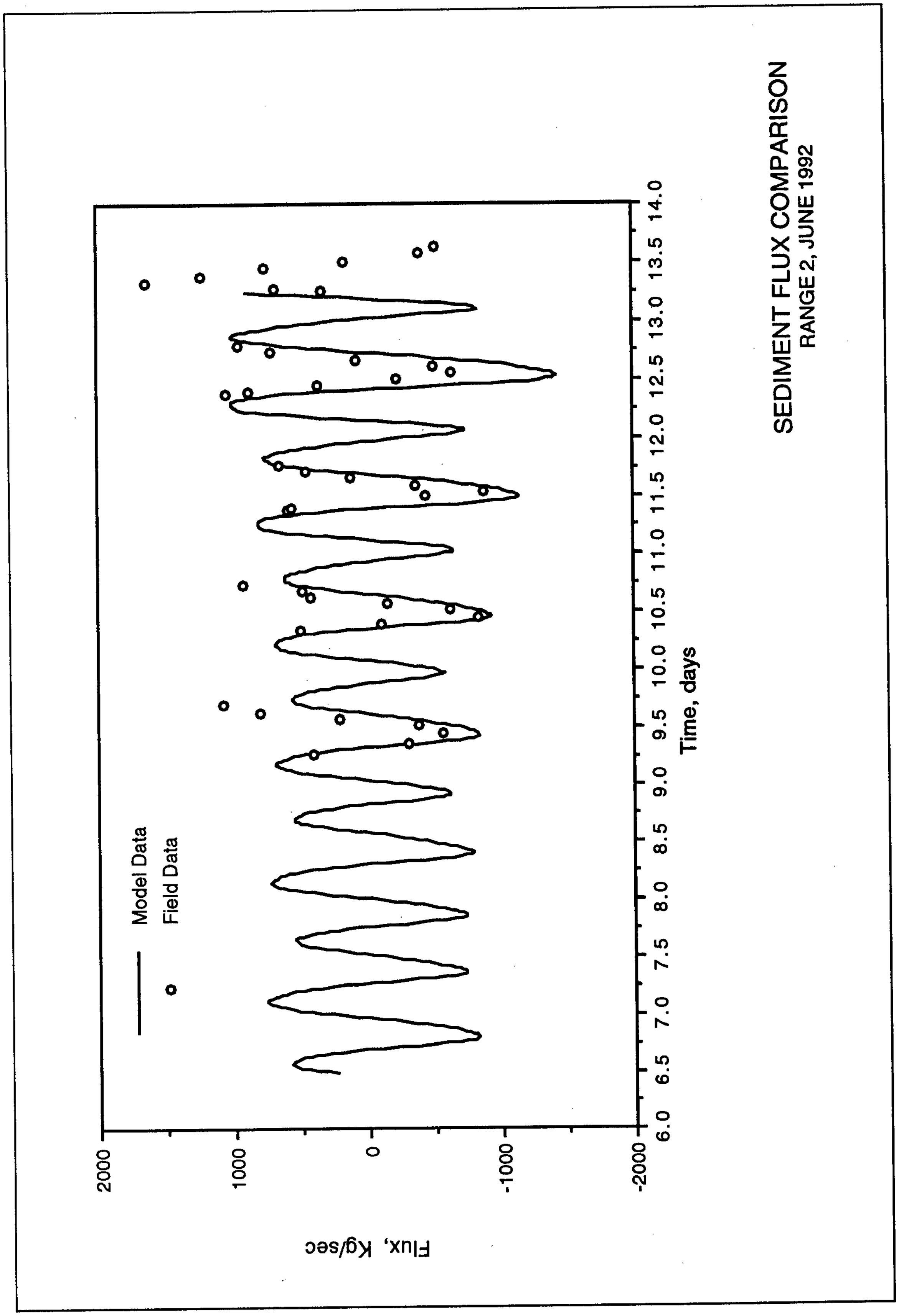
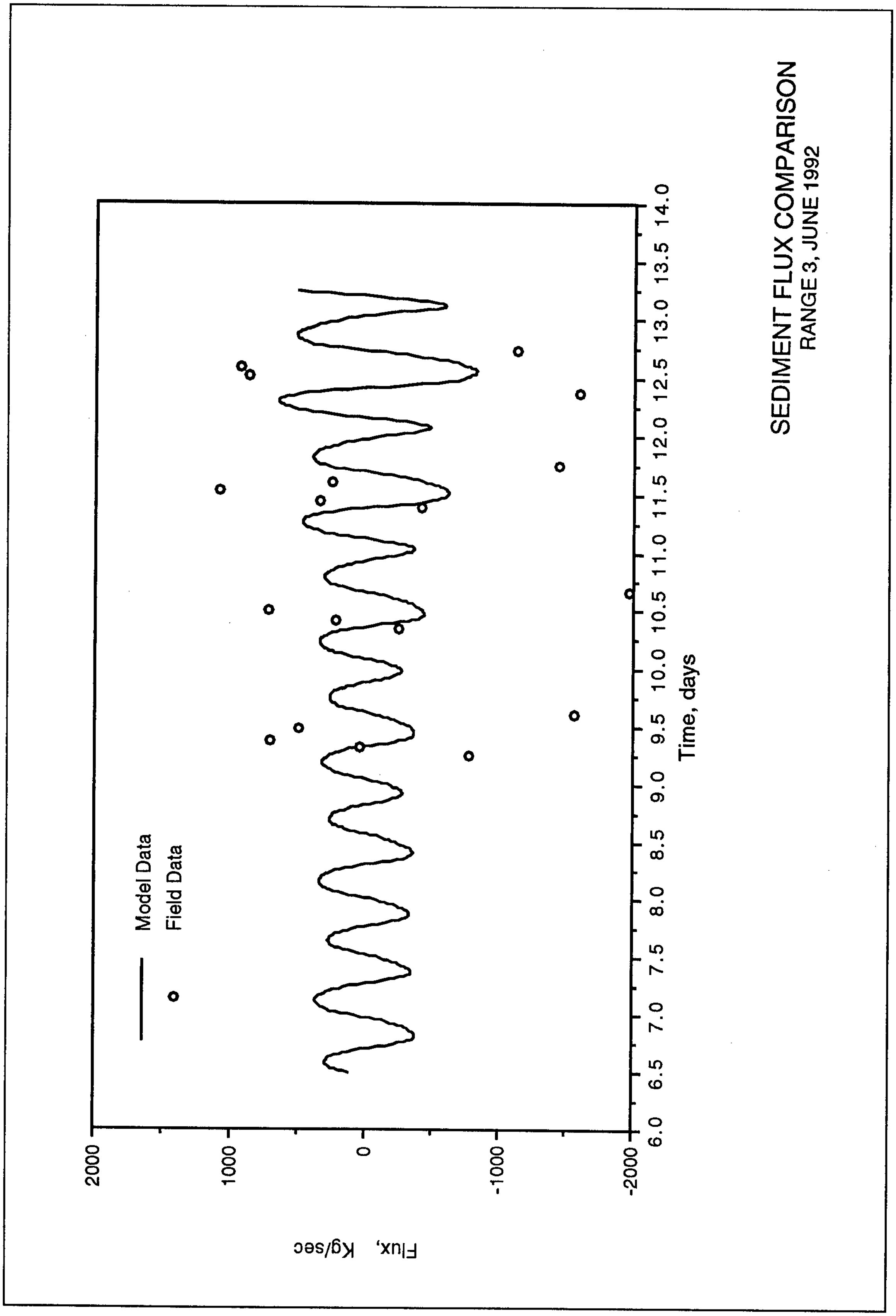

SEDIMENT FLUX COMPARISON
RANGE 2, JUNE 1992
Model Data
Field Data
Flux, Kg/sec
Time, days
2000
1000
0
-1000
-2000
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0
11.5
12.0
12.5
13.0
13.5
14.0

Plate 16


SEDIMENT FLUX COMPARISON
RANGE 3, JUNE 1992
Model Data
Field Data
Flux, Kg/sec
2000
1000
0
-1000
-2000
Time, days
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0
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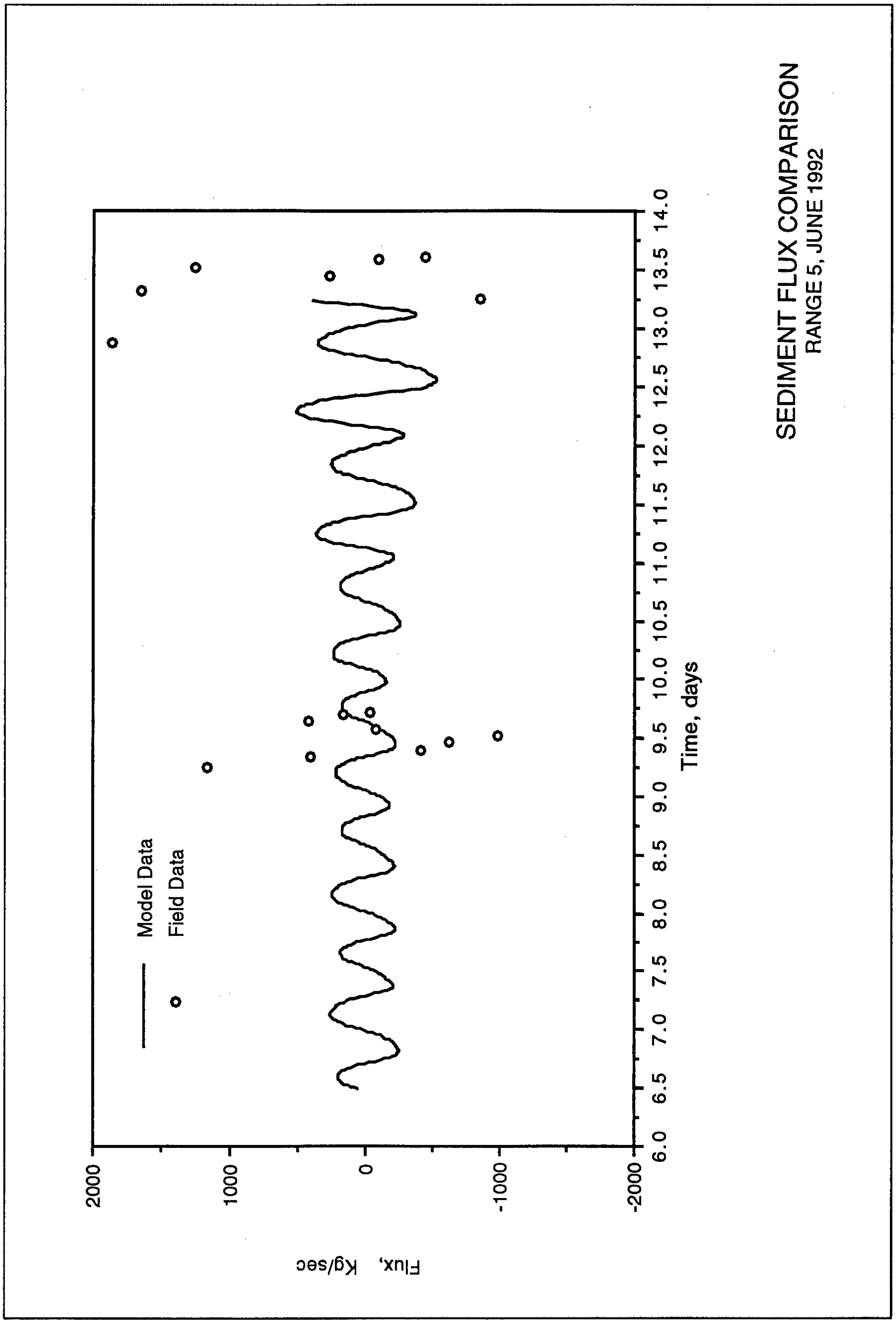
12.5
13.0
13.5
14.0

Plate 17


SEDIMENT FLUX COMPARISON
RANGE 5, JUNE 1992
Model Data
Field Data
Flux, Kg/sec
Time, days
2000
1000
0
-1000
-2000
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0
11.5
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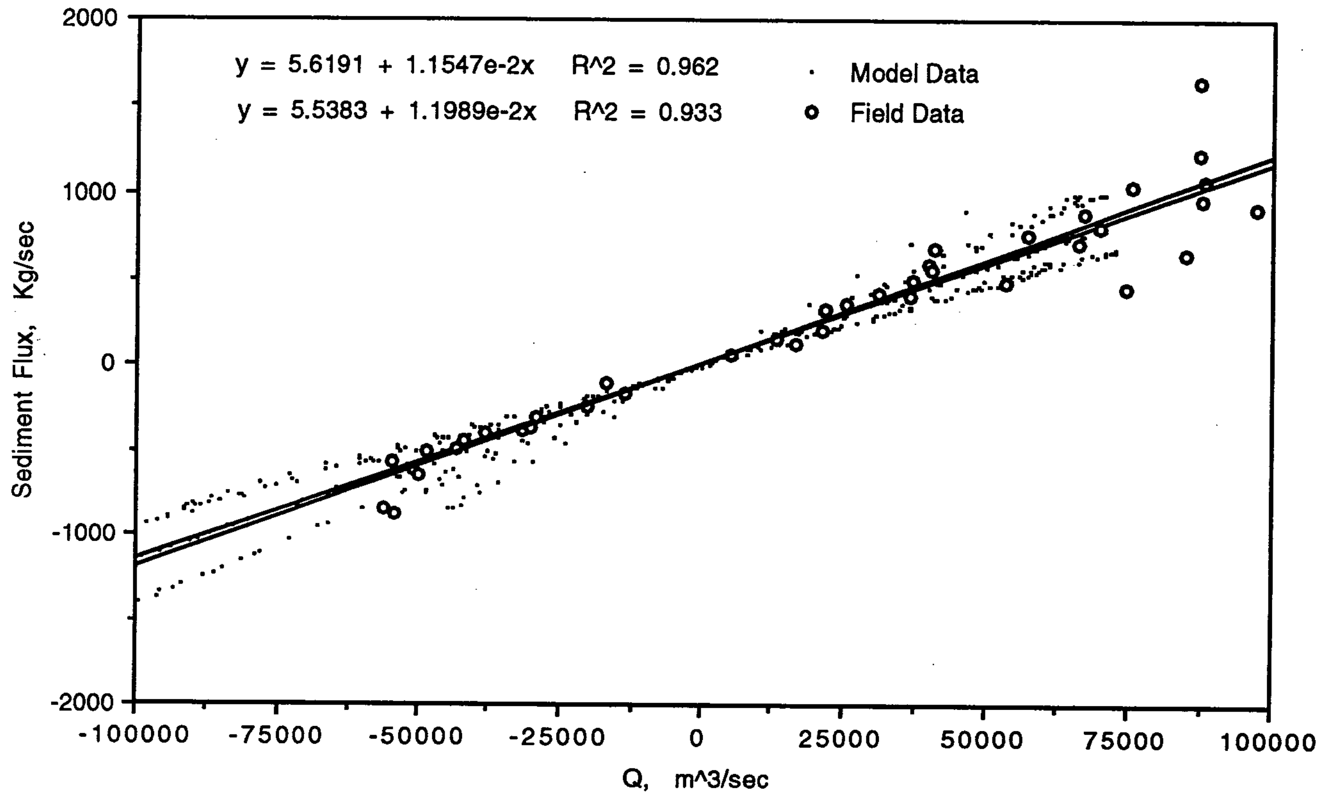
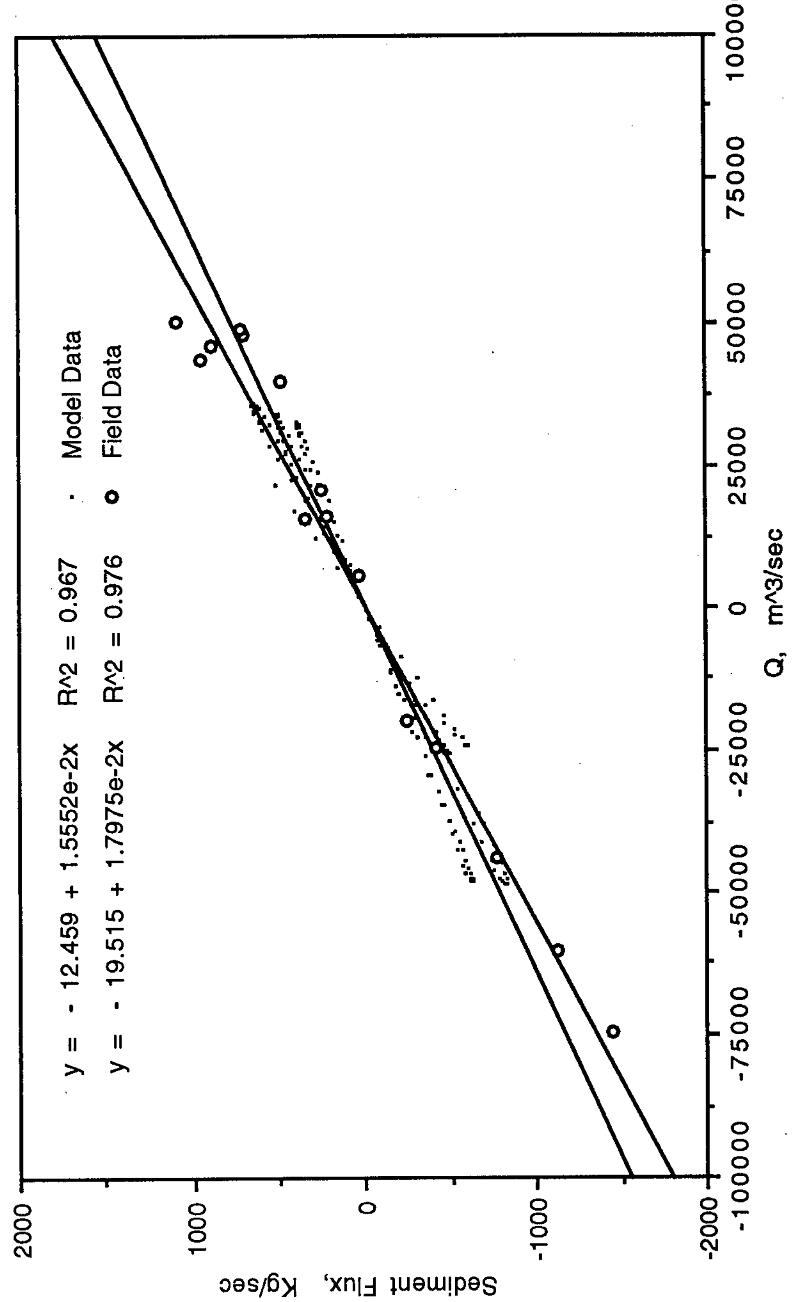
13.5
14.0

Plate 18

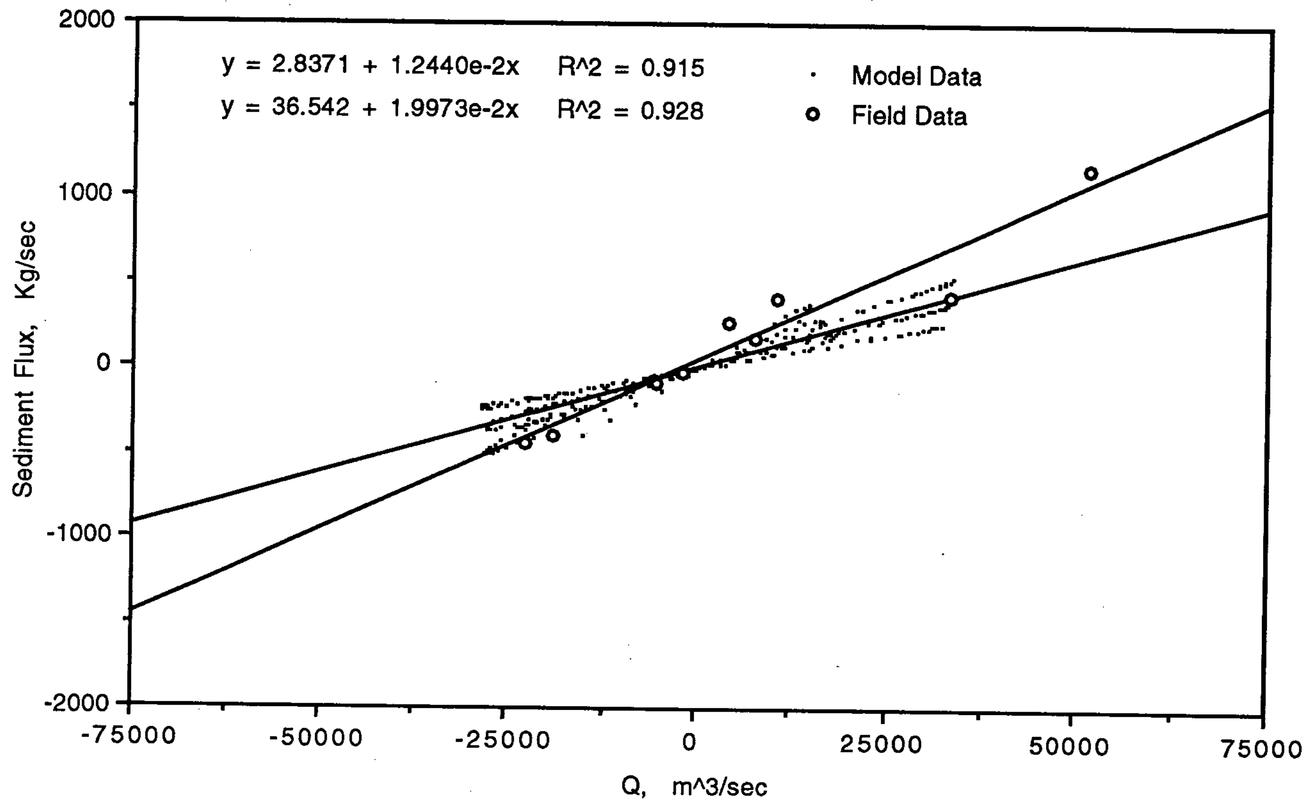


SEDIMENT FLUX AND WATER DISCHARGE
COMPARISON FOR THE MODEL AND FIELD DATA
RANGE 2, JUNE 1992



SEDIMENT FLUX AND WATER DISCHARGE
COMPARISON FOR THE MODEL AND FIELD DATA
RANGE 3, JUNE 1992

Plate 20



SEDIMENT FLUX AND WATER DISCHARGE
COMPARISON FOR THE MODEL AND FIELD DATA
RANGE 5, JUNE 1992

Appendix A
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13. ABSTRACT *(Maximum 200 words)*

Field data analysis was used to examine suspended sediment transport in Central San Francisco Bay, and to develop and verify a two-dimensional numerical fine-grained sediment transport model. This study concerned the dispersion and fate of disposed dredged material in Central San Francisco Bay, California. The 1992 monitoring survey spanned a 2-week period in June, and used three boat-mounted acoustic Doppler current profiling (ADCP) systems to obtain repeated cross-sectional transects near the Golden Gate, the entrance to South Bay, and Richmond Point. Between acoustic transects, water samples were obtained over depth for salinity, total suspended material (TSM) concentration, and particle size determinations. Acoustic backscatter data were used to produce correlated suspended material concentration and flux fields. Discrete measurements were fit to empirical discharge and suspended flux models and integrated over a neap-spring-neap tidal sequence to estimate net transport.

There was an observed net transport of suspended sediment seaward at the Golden Gate over the neap to spring sampling period. The total net transport was 188×10^6 kg (188,000 metric tonnes) seaward over 14 lunar days. Fluxes during the ebb flows averaged 44 percent greater than the flood flows, and instantaneous strong-ebb TSM fluxes were often more than twice those on flood tidal phases.

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Suspended sediment concentrations increased during the strongest part of the ebb at all Central Bay sampling ranges. Wind forcing did not appear important to this process. Suspended concentrations quickly returned to normal levels after the passage of peak ebb flows. Spatial variability in the TSM fields was relatively large. The ADCP backscatter intensity measurements correlated well with TSM especially on the Golden Gate range where a broadband unit was employed.

The numerical sediment model reproduced the tidal flux across ranges adequately. Instantaneous TSM concentrations at a point were less well predicted by the model as was temporal variability. The model did not fully capture TSM variability. The model should be a useful tool in predicting general transport patterns in Central Bay.